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Representational momentum, internalized dynamics, and perceptual adaptation

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In this paper I look at dynamic mental representations, motion detection under conditions of certainty or uncertainty, perceptual adaptation, and priming of motion direction. The goal is to bridge the boundaries created in part by the use of different terminology within different literatures. The most fruitful parallel may be between the phenomenon of dynamic mental representation and representational momentum on the one hand, and perceptual adaptation as revealed by motion priming on the other. I suggest an overlap between the two phenomena.

The term representational momentum was introduced by Freyd and Finke in 1984 and refers to both a phenomenon and a theory. If an observer views a target undergoing motion (including implied motion and apparent motion), after the target disappears the remembered final position will be shifted in the direction of motion (for a review, see Freyd, 1992; Hubbard, 1995b). The original theory and more recent versions will be discussed in more detail later, but, as the name suggests, the memory distortion is taken as evidence of a change in the represented position of the target. More specifically the word momentum refers to a property of the representation that mirrors a property of the physical world.

After the early optimism and theoretical debate, relatively slow progress has been achieved recently in understanding representational momentum. Although more empirical work is ongoing and necessary, in this paper I take a different approach and look at a larger set of phenomena and theories, from dynamic mental representations, motion detection under conditions of certainty or uncertainty, perceptual adaptation, aftereffects, through to priming effects of motion. The aim of this paper is to compare phenomena and theories

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that come from different literatures in the hope of moving beyond the sharp divisions potentially created by habit and by differences in terminology.

DYNAMIC MENTAL REPRESENTATIONS

One motivation for this paper is a personal dissatisfaction with the use of the principle of internalized dynamics, i.e., the internalization of physical forces, as opposed to internalization of physical laws. This is a personal opinion, which I want to acknowledge up front. Hopefully these concerns will seem more justified by the end of the paper. The idea that representational momentum, as well as representational gravity and friction, is an internalization of aspects of the physical world is at the heart of the theoretical discussion in the literature, and it is common to both Freyd's original model (Freyd, 1987, 1992) and Hubbard's model, which is wider in scope and explain a larger set of data (Hubbard, 1999). After its introduction by Shepard (1984, 1994), the principle of internalization has been very influential, but the reader who is interested in a critical evaluation of its legacy should read the recent special issue of *Behavioral and Brain Sciences* on this subject with contributions by Barlow (in press), Hecht (in press), Kubovy and Epstein (in press), Schwartz (in press), Tenenbaum and Griffiths (in press), and Todorovic (in press).

The relevant issue here is not internalization *per se*, rather the internalization of forces (dynamics). Dynamics is the branch of mechanics that studies forces and their effect on the motion of bodies. In classical mechanics a force is merely a theoretical construct to refer to a cause of motion or transformation.[1] If a force is a cause of motion, a motion may be seen as the signature of a force. To some extent, forces are specified visually by kinematic information—the way bodies move. Classic work on perception of dynamic information carried out by Michotte (1946/1963) suggests that there is a direct perception of forces, in the sense of a perception of causes not mediated by explicit knowledge about the event: Observers do not *know* that an object colliding with a second one sets the second in motion, they do *see* it. However, perceived forces are not congruent with the forces that classical mechanics uses to explain motion of bodies. The extent of the human ability to perceive dynamics—forces, masses, and the like—is debated in the literature, but it appears to be limited (Kaiser & Proffitt, 1987; Proffitt & Gilden, 1989; Runeson & Frykholm, 1983).

However, even though the perception of dynamic information is limited, we can agree with Michotte that causes of motion (forces) can be perceived. But to argue that such causes are perceived because the forces have been internalized adds another step to the argument and is in danger of circularity (Epstein,

[1]Sometimes dynamics is divided into kinematics and kinetics. Kinematics is the study of the geometry of motion, i.e., position, velocity, and acceleration of an object. Kinetics is the study of motion in terms of the underlying forces.

1993). The motivation for this paper then, is to try and describe the available data without reference to internalized forces, or perhaps even without reference to internal representations. In the rest of this first section I will review empirical studies about dynamic mental representations.

Dynamic information in static displays

I will first consider context effects on memory for position. In other words, motion is suggested by the context but the target is not actually presented in motion. This is an ideal test situation to compare perception of statics and dynamics (Freyd, Pantzer, & Cheng, 1988).

Static displays, like simple drawings or photographs, can produce a perception of a dynamic event. Researchers have examined the effect that the information present in static displays has on judgements of position of objects (Bertamini, 1993; Freyd, 1983; Freyd & Pantzer, 1995; Freyd et al., 1988; see also Senior, Ward, & David, this issue). These studies use static images where motion is implied by gravity or other forces in the configuration (as when a spring is pressed by a weight). For example, the observer is asked to judge whether two photographs of a person depicted in the act of jumping from a wall were the same or different. When the person in the photograph is displaced downwards reaction times are longer than when the person is displaced upwards (Freyd, 1983). That is, a displacement downward is harder to detect. In another experiment, observers were presented with drawings of meaningful objects embedded in dynamic events. For example, the observer saw a flower vase on a table, then a flower vase without support, and finally the observer was asked to choose one of two alternatives: Was the flower vase in the same position, or had it been displaced. Downward displacement (in the direction implied by the event of falling) was detected less often (Freyd et al., 1988). An inverted U-shaped function describes the proportion of times that observers failed to detect the change for different amounts of displacement, from a large displacement upward to a large displacement downward. The peak of this function shows the position where the perception of change (displacement) is least likely to occur. This point is systematically shifted in the direction of a displacement consistent with the natural interpretation of the display, i.e., the implied gravitational attraction.

Freyd and Pantzer (1995) used images where motion was implied by the apparent "pointing" of an object. For example, an isosceles triangle points in the direction of the smaller angle. Using static arrows, triangles, and other oriented shapes, Freyd and Pantzer found that memory for position was distorted in the direction that the object appeared to point. These results are similar to the case discussed above where motion is implied by gravity (e.g., Freyd et al., 1988). These data are taken to show that the representation of the position of the object has changed in the brief retention interval before the presentation of the probe. The original object is now represented in a different position, and displacing the probe object by exactly that amount will be perceived as keeping the object still. The rationale is that time is represented by a dimension that has similar properties to external time (Freyd, 1987). There is an automatic anticipation of any event and in the absence of information to the contrary, the event evolves along the time dimension in a way consistent with the type of transformation that was represented.

Bertamini (1993) used an object placed on an inclined plane to suggest a rolling event. More specifically, he studied the case of a ball rolling downwards on a plane but only one variable—the inclination of the plane—suggested motion. By changing the angle of inclination and the retention interval Bertamini tested the relationship between physical and representational laws quantitatively. Representation is distorted in a way consistent with the physical laws only when the retention interval is short—less than 300 ms (consistent with Freyd & Johnson, 1987). Within this range there is an effect of the inclination of the plane, an effect of the retention interval, and an interaction of these two variables. This is consistent with laws of classical mechanics, but for the fact that the effect of time was linear instead of quadratic. The presence of friction in this context may have influenced the effect of inclination as suggested by Hubbard (1995b) but does not explain the non-monotonic effect of time.

Representational momentum using a series of displays

When presented with a moving object, or with an object presented in a series of positions consistent with motion in a single direction (e.g., rotation around its centre), observers make systematic mistakes in judging its final position (Freyd & Finke, 1984). In a typical experiment observers are asked to compare the final position of an object to the position of a probe object presented subsequently. They tend to detect faster and more accurately changes in position that are in the direction opposite to the previous direction of motion (Freyd & Finke, 1984). The basic representational momentum paradigm is illustrated in Figure 1.

It is important to keep in mind the similarities and the differences between the experiments with static displays, described before, and the representational momentum experiments. In the former case a static display of an object in a meaningful context is presented. Then memory shifts are tested with a probe object displaced either in the expected or in the unexpected direction. Given that the task is to detect the displacement, the term static display is proper only if one disregards the displacement between the first display and the probe. In the case of representational momentum, instead, an object (or a configuration) is presented in different positions. After the last presentation a probe is used to test memory exactly as in the case of the static display.

Representational momentum has the following characteristics: (1) It depends on coherent implied motion, because if the order of presentation is

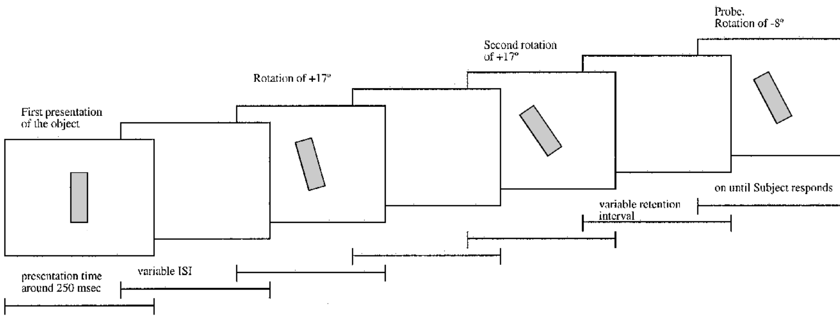

Figure 1. In a typical representational momentum experiment, an object is presented in a sequence of discrete positions. In this example (adapted from Freyd & Finke, 1984) the object rotates by +17° in each frame. Depending on the timing of the ISI the motion can be simply implied, or can be perceived as a smooth rotation. The probe in the final frame can be rotated either in the same or in the opposite direction with respect the induction phase. In this example the probe is rotated by –8°. Observers decide whether the probe object is in the same position as the object in the last frame (same), or whether it has changed position (different).

shuffled and therefore the change of position is not consistent with motion, the effect disappears (Freyd & Finke, 1984); (2) it does not depend on sensory motion detectors, because it is observed even when the temporal parameters are beyond those for apparent motion; (3) it is impervious to error feedback, and to explicit knowledge of the result expectations (Freyd, 1987), although there is evidence that cognitive factors may be important (Hubbard, 1994, 1995b; Reed & Vinson, 1996; Vinson & Reed, this issue); (4) the distortion increases with the retention interval—at least for the first 300 ms (Freyd & Johnson, 1987); (5) the distortion depends on implied velocity (Hubbard & Bharucha, 1988), but when probes are used (as in Figure 1) the effect is small and requires a wide range of positions of the probe to be detected (Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986; Freyd & Finke, 1985); (6) the distortion is attached to the represented object, and disappears when the object is substituted with a new object having a different shape. When a similar object with a different texture is used the effect is reduced (Kelly & Freyd, 1987); (7) the effect is present also for scaling of the object (Kelly & Freyd, 1987) and movement in depth (Hayes, Sacher, Thornton, Sereno, & Freyd, 1996; see also Munger & Minchow, this issue; Munger, Solberg, Horrocks, & Preston, 1999).

Representational momentum resulting from a series of displays can be explained by the same hypothesis discussed earlier in relation to static displays. When an object is perceived as moving, and/or it is represented as moving, the representation has a momentum. Thus, as in classical mechanics, representations tend to preserve their status (i.e., motion) unless new forces are applied to them. There is an internalization (not necessarily innate) of physical and/or biological laws of motion (Freyd, 1992; Hubbard, 1995b; Shepard, 1984). This representational momentum is a necessary characteristic of a system with spatiotemporal coherence. It should work for any continuous change in any dimension, and is an adaptive anticipatory computation (Freyd, 1992). Similar forward memory distortions have been reported for some dimensions unrelated to motion, such as pitch (Freyd, Kelly, & DeKay, 1990) but the opposite effect has been reported in some other dimensions, such as expressions of faces (Thornton & Freyd, 1998) and brightness (Brehaut & Tipper, 1996; Favretto & Hubbard, 2000).

Given the characteristics of the memory shift, Freyd has suggested that the phenomenon is modular, in the sense of independent of cognitive expectations or explicit knowledge about the event. However, Hubbard and Bharucha (1988), Ranney (1989), and Reed and Vinson (1996) found evidence suggesting that representational momentum is a cognitive process. Memory shifts are in the direction of anticipated motion: In the case of an object directed toward a wall the distortion is not in the direction of motion if observers expect the object to bounce (Hubbard & Bharucha, 1988). As Hubbard concluded in 1993, the issue of how much cognitive factors play a role is still open.

In this section I described representational momentum mainly with respect to the paradigm that uses discrete changes of position (see Figure 1). I have, however, mentioned that the same memory distortion can be measured using a smoothly moving object (this methodology was used for example by Hubbard & Bharucha, 1988). This difference in methodology is not central for the purposes of this paper, and I will focus on discrete motion. One reason to do so is to avoid the likely intrusion of eye tracking effects which need to be considered when observers are asked to track the moving object before it disappears. Kerzel (2000), has shown recently in a series of experiments that eye movements can explain some of the findings with smooth motion.

Differences between internalized physics and naïve physics

Naïve physics is a research area (for a review see Bozzi, 1990; or Smith & Casati, 1994) concerned with people's beliefs and understanding of the physical world. In particular, beliefs about the motion of objects have been studied extensively (e.g., Hecht & Bertamini 2000; McCloskey, Caramazza, & Green, 1980). It is natural to ask whether we can find evidence for internalized dynamics in such beliefs, or evidence for a parallel between mistakes in people's belief system and memory distortions about position.

The first important and surprising observation is that the forces of classical mechanics are not the best predictor of the distortion in judging the final position of an object. For a ball at the end of a curved spiral tube the distortion is largest when the ball moves along the curved path, and not when it moves along the tangent as one would expect from the laws of mechanics (Freyd & Jones, 1994). However, a curvilinear response is made by a large number of naïve observers in a paper-and-pencil task (McCloskey et al., 1980). There is, therefore, a similarity between the strength of representational momentum and naive beliefs about motion. This is also supported by the findings of Kozhevnikov and Hegarty (1999). In their experiments memory distortions were larger (downwards) for larger free-falling objects, but smaller (upwards) for the larger objects when they moved against gravity. Again, this finding is consistent with people's beliefs but not with Newtonian physics.

Why does the representation behave in a way consistent with naïve physics? According to Finke and Shyi (1988), the representational momentum theory predicts that even when the anticipated pathway of motion is physically incorrect the memory shift should be consistent with it. In the case of both naïve physics and representational momentum one can talk of internalization, even though the process of internalization may lead to internalized principles that are different from those used by theoretical physics. In other words, the regularities in people's experience are the driving force of adaptation and internalization. For example, friction and drag will always be part of people's experience of motion, therefore some of the Aristotelian and mediaeval ideas about motion may be intuitively more useful than Newtonian physics (not to mention quantum mechanics). This argument has been developed by Hubbard (1996, 1999) who introduced the environmental invariants hypothesis. Invariants in the environment include gravity and friction (Hubbard, 1995a). He explained the data from the curved tube experiment by combining representational momentum with a decaying representational centripetal force.

The power of the concept of internalisation is currently debated in the field of naïve physics, and beliefs have been found that do not seem to conform to this notion (Hecht & Bertamini, 2000; for a more theoretical discussion see Hecht, in press). With respect to representational momentum and its similarity to naïve concepts of momentum, a serious problem is that people presented with animated displays of alternative paths of balls escaping from a C-shaped tube do not make the prediction errors that they make in the paper and pencil task (Kaiser, Proffitt, & Anderson, 1985). Therefore the memory shift is not only inconsistent with classical mechanics, but it is also inconsistent with perceptual judgements of dynamic events.

It appears that the best predictor of the memory shift is the general pattern of motion of the object. Similarly to what happens with the C-shaped tube, for a rectangle at the peak of a sinusoidal motion the distortion is along the sinusoidal, not the tangent path (Verfaillie & d'Ydewalle, 1991). The problem of a discrepancy between the dynamic interpretation of the event, and the kind of distortion observed for the object position, leads to the conclusion that the laws of classical mechanics and the laws of perception are different. In other words, even though we may perceive forces, such forces are different from those described by physics (Hubbard, 1999). This is probably not a controversial point, but one of its implications is that it makes much less clear what the adaptive meaning of this perceptual anticipatory computation is. In the specific case of a distortion in the perceived position of the object, where is the advantage of anticipating the position if this anticipation is not tuned to the laws of the surrounding environment?

Representational momentum as a memory phenomenon

A question that cannot be evaded with respect to representational momentum and representation of environmental invariants is the meaning of the word representation. Freyd's theory (1987, 1992) of dynamic mental representations explains longer reaction times and more errors in detecting change of position. It does so by hypothesizing a change in the inner representation that coincides with the actual change in the stimulus display. The probe presented after the retention interval is displaced forward, but because of a momentum in the representation of the object the representation itself has changed forward. Although the term "momentum" is a metaphorical way of describing what happens to the representation, it is a good way of describing a change in the direction of motion due to the fact that (in the absence of information about what happened to the object) the transformation of the representation does not stop instantaneously. Hubbard's environmental invariants hypothesis (Hubbard, 1999) is different in that it includes more anticipatory forces, such as gravity and friction, but uses the same concept of internal representation.

This argument is sound with respect to a memory trace, but the representational momentum shift exists for retention intervals as short as 10 ms, and it decays after 300 ms (Bertamini, 1993; Freyd & Johnson, 1987). For a perceptual process there is a possible paradox here. If by representation we mean the substrate of a perceptual act then the transformation of the representation must correspond to the transformation of our perceptual experience. In other words, if a change in object's position (forward) is represented, why is the change in position (forward) not perceived or detected? How can representing a change lead to failure to detect such change?

One solution is that the dynamic representation theory refers to a representation in memory, that is instrumental to the final perception of an event but different from the representation of the event. This representation is knowledge about the object (for example direction of motion and speed) that is updated by sensory information, but is otherwise independent of it. An alternative solution is to describe the failure to detect change not as a memory effect, but as a perceptual adaptation effect.[2] The next session considers this possibility.

[2]Another issue outside the scope of this paper is whether the target is *perceived* as moving farther than its final position. This may be a process of extrapolation based on internalized principles, and if so it is incompatible with an adaptation process. However, it would also move away from any statement about the inner representation. Some evidence to support this view exists, such as the overshooting effects of moving targets (Foster & Gravano, 1982; Sinico, 2000).

ALTERNATIVE EXPLANATIONS

I have presented data about memory for position, either using static displays or an object undergoing implied or apparent motion. In both cases the remembered final position can be tested using a probe. I have also presented theories that say that the memory shift is due to a change in the represented position over time (Freyd, 1987; Hubbard, 1995b). I will now turn to some possible alternative explanations, trying to stress both their advantages and their disadvantages. The goal of this paper is to compare phenomena that have been described in different terms. This section is therefore titled alternative explanations only in order to compare phenomena. I will try to see if the findings discussed so far can be described in a similar way to other phenomena, and in particular the phenomenon of adaptation.

The literature reviewed in the first part of the paper is concerned with distortions of memory for position of an object, to test memory for position researchers in this field use either a probe (e.g., Kelly & Freyd, 1987) or a cursor positioning technique (e.g., Hubbard & Bharucha, 1988). In this second part of the paper I describe a larger literature concerned with sensory adaptation, leading to aftereffects, and motion contrast. Table 1 breaks down these literatures into four areas, which are listed for the purpose of clarity. In the following sections I will explore in further detail their relative strengths and weaknesses, especially with an eye to discover a possible overlap of the phenomena described.[3] However, before considering adaptation I will show that effects of expectations on detection of a displacement are not a good model for the data.

In the studies about internalization of dynamic information (e.g., Freyd, 1983; Freyd & Finke, 1985; Hubbard, 1995a; etc.), it is possible that the implied direction of motion present in the display had given information to the observers, and that the observers were faster to respond when the displacement was different from their expectation (see Kerzel, this issue, for another

[3]One effect not listed in Table 1 is visual motion momentum. This is because, although the name may cause confusion, visual motion momentum is a completely different phenomenon from representational momentum. When something is presented as moving in one direction and it is followed by a directionally ambiguous displacement, the motion is perceived to continue in the same direction (Ramachandran & Anstis, 1983). For example, using four dots in a diamond configuration, each pair can be lit alternatively and the direction of apparent motion is ambiguous. However, if other dots are presented in apparent motion with one of the pair, the motion continues in the same direction. Ramachandran and Anstis (1983) suggest that visual momentum is due to a feed-forward facilitation in the neurones responsible for perception of motion. If representational momentum, and in general poor detection of displacement in the expected direction, is explained by an inhibitory response to the transformation of the object, there are two responses that pull in opposite directions. The problem is not in accepting the existence of both facilitation and inhibition rather the problem is in defining where one should expect the one and where one should expect the other. This problem, also in the form of motion capture/motion contrast, motion integration/motion differentiation, is central to the study of motion perception (Braddick, 1993).

TABLE 1
A summary of four areas in the literature that deal with different but potentially related phenomena

	Momentum of representation/ dynamic mental representation	*Environmental invariants*	*Sensory adaptation/ recalibration*	*Perceptual adaptation/ motion contrast*
Origin	Freyd and Finke (1984)	Hubbard (1999)	Andrews (1964)	Raymond (2000)
Typical methodology	Forced-choice about change of position	Cursor positioning	Neutralizing technique	Motion priming
Role of attention	Presumably no (modular)	Presumably yes (cognitive)	No	Yes
Domain	Any continuum with spatiotemporal coherence	Any environmental invariance	Many stimulus dimensions but constrained by sensory physiology	Motion

perspective on expectation). Note that although the task was not explicitly defined as a detection of displacement, displacement was the only change that subjects were asked to detect. It is therefore not unreasonable to describe this task as a detection of displacement (or motion depending on the parameters).

Perhaps the motion in the expected direction did not appear as salient as the motion in the opposite direction, i.e., the violation of the expectation creates an arousal that quickens the response. If by expectation we mean decreased uncertainty, this explanation is problematic when considering that, albeit using a different paradigm and studying a different problem, Ball and Sekuler (1980, 1981) showed that direction uncertainty increases reaction time. Therefore observers should be slower to respond when the displacement is not coherent with their expectation, the opposite of what is observed.

According to Ball and Sekuler (1980), the loss in sensitivity to motion onset is caused by a mechanism whose peak sensitivity is to a direction midway between all possible directions. In a series of experiments, observers saw a pattern of dots, and pressed a key as soon as the dots moved. In the *direction certainty* condition, the direction was always the same, and observers were aware of that. In the *direction uncertainty* condition, two or more directions were possible. This effect of direction uncertainty on reaction time for responses to motion onset is present also for responses to change of direction (Sekuler, Sekuler, & Sekuler, 1990). To explain these findings, Dzhafarov, Sekuler, and Allik (1993) have proposed that changes in velocity (including onset and offset) are detected by special-purpose mechanisms. These mechanisms use a subtractive normalization to reduce the detection of changes in velocity to the detection of motion onset. Dzhafarov et al. (1993) believe that this mechanism is similar, but different, from sensory adaptation for two reasons: (1) This mechanism is based on a readjustment of weights that is not part of the encoding process *per se*; (2) This mechanism is task-specific. In other words it is a special-purpose computation used to answer a particular question about visual motion.

Static displays of objects in meaningful contexts certainly convey information that creates expectations in the observers. Even more so when implied or apparent motion is used. Why then did these expectations have the opposite effect than the knowledge of the direction had in Ball and Sekuler's (1980) experiment (see also Kerzel, this issue)? I will now consider the possibility that these findings, instead of being effects of expectation, are effects of some kind of adaptation.

Displacement aftereffect

Can errors in recognizing that a probe object has been displaced forward be due to an aftereffect? It may seem that a negative aftereffect should move the representation backward instead of forward along the path of motion, therefore an aftereffect is opposite in direction to the forward displacement of the representation (Freyd & Finke, 1984). However, an aftereffect does not displace the representation but instead alters the sensitivity of the system. Let us consider a typical representational momentum experiment, and particularly the task of the observer. For the moment and for the sake of argument, let us assume that the system is affected by a motion aftereffect. The probe object that is presented further along the path of motion is displaced in the same direction of the inducing motion. Sensitivity for this direction of motion is depressed and therefore the object is less likely to be perceived as displaced. Conversely, backward motion is reported more often.

Threshold elevation for perception of motion in the same direction presented during adaptation is one of the aspects of motion aftereffects (Bonnet, Le Gall, & Lorenceau, 1984; Sekuler, 1975). To measure an aftereffect, a probe can be used and the observer asked to manipulate its position so that it will appear stationary. The observer adjusts the probe position in the direction of motion of the inducing pattern to compensate for a perception of motion in the opposite direction. This is called a neutralizing procedure. Moreover, it has also been shown recently that position can be misperceived after exposure to motion (Snowden, 1998; Whitney & Cavanagh, 2000, this issue). A displacement (as opposed to motion) aftereffect would therefore be similar to representational momentum, or even another name for the same effect. This idea applies to transformations in other continuous dimensions as well. The problems are (1) Why would implied motion (e.g., a sequence of displacements) induce an aftereffect in the same way that motion does?; (2) the presentation of the implied motion is short and it is not clear whether adaptation can happen this quickly (for an example of fast perceptual learning see Poggio, Fahle, & Edelman, 1992); (3) an aftereffect *per se* does not explain the effect of the context in static displays.

Perceptual adaptation

Apart from sensory adaptation and fatigue of opponent motion mechanisms, a perceptual adaptation (i.e., exposure to a certain pattern of motion) can also lead to a change in sensitivity that is linked to visual selection and attention (Raymond, 2000; Raymond, O'Donnell, & Tipper, 1998). Such recent findings are particularly interesting because they use a priming paradigm. Similarly to a typical representational momentum paradigm, motion is presented for a brief period of time (e.g., half a second) then a blank is presented (e.g., 200 ms) and then a probe is used and observers report direction of motion. By using a large number of dots and varying the percentage of dots moving in one direction, the perception of motion in one particular direction is made more or less easy to detect. Moreover, the display may include two transparent motions: When two sets of dots move in orthogonal directions (upward or downward and leftward or rightward) they appear as two translucent sheets of dots. Attention can be manipulated by asking observers to attend to one of the two transparent components of motion. In the words of the authors "attention to one direction causes a loss in sensitivity to that direction in a subsequent event" (Raymond et al., 1998, p. 2867). This sentence could apply directly to the phenomenon of representational momentum, where the subsequent event is the displacement of the probe.

Raymond et al. (1998; Raymond & Isaak, 1998) prefer to call this effect a motion direction contrast, because it does not vary with the duration of the retention interval and because it requires attention. Therefore they argue that the effect does not depend on the activation of motion detectors. If so, the fact that motion is not actually seen in the representational momentum experiments is not an obstacle to seeing a link between the two phenomena. This effect can be described as priming, and both the inducing displacement in a representational momentum experiment and the context in a static display suggesting a dynamic event can also be described as primes. Similarly, effects of gravity and friction on memory for position (Hubbard, 1995a; Nagai, Kazai, & Yagi, this issue) could also be considered priming effects. I will use the term perceptual adaptation in this context rather than the term direction contrast used by the authors (Raymond et al., 1998) to stress the fact that the effect depends on a previous presentation of motion. I will use the phrase sensory adaptation in the context of motion aftereffects. Therefore, the sensory adaptation described in the previous section, and the perceptual adaptation described in this section are different and should not be confused. The first is based on the existence of a displacement aftereffect, the second is based on a form of non-sensory adaptation that requires attention.

Recalibration and associative learning

Among the characteristics of representational momentum, there is the fact that the distortion is attached to the represented object (Kelly & Freyd, 1987). This is also the prediction in a contingent adaptation: The distortion is contingent on the features of the object. For instance, motion aftereffects have been proved to be long-lasting and form-sensitive (Bonnet et al., 1984; Favreau, 1979, 1981). Instead of an internalization of the laws of mechanics or other ecologically relevant laws, the contingency of a configuration with a pattern of transformation can produce an adaptation linked to that context. This section describes some theoretical issues concerning interpretation of visual contingent aftereffects. This literature is massive, so this will only be a summary of the difference between the main classes of theories. In 1965 Celeste McCollough described a colour aftereffect contingent on line orientation. In the paradigmatic experiment, the observer is presented with a black and green horizontal grid, alternating with a black and magenta vertical grid. Later, black and white assessment grids appear to be coloured with the complementary colour. For example, the horizontal grid appears pinkish. Since then, many contingent aftereffects have been described in different domains. I will briefly consider three kinds of theories trying to explain these phenomena.

Fatigue of receptors. Receptors are organised antagonistically and therefore if one response is lowered by extensive activation, the relative strength of the other response is increased (Harris, 1980; McCollough, 1965). However, contingent aftereffects last for weeks, and show extinction and spontaneous recovery (Bonnet et al., 1984). Time is not a good predictor of the decay of the aftereffect strength, visual stimulation with a similar pattern is more effective in extinguishing the aftereffect than a dissimilar or poor stimulation (MacKay & MacKay, 1975; Skowbo & Clynes, 1977) and the decay function for contingent motion aftereffects is non-monotonic (Favreau, 1976).

Recalibration. Andrews (1964) proposed that the visual system is continuously correcting for errors. The definition of error is based on a genetically prescribed statistical criterion. For example, in the case of motion the criterion could be that the average movement over a period of time for every element in the visual representation is zero. This is equivalent to assuming that in the visual field any direction of motion is equally likely. The system adjusts for discrepancies between its assumptions and the input, and therefore we observe aftereffects (Dodwell & Humphrey, 1990). The idea of normalization to explain figural aftereffects is also found in Gibson, the first to describe such phenomenon (Gibson, 1933).

According to Barlow (1990) modifiable inhibitory synapses can change the response of a set of neurones. Therefore not only the response to a frequently presented stimulation, but also the response to a joint occurrence of two (or more) stimulations can adapt. The functional role of this adaptation is in the need to base the internal definition of what is normal on past experience. The adapted system is now most effective in presenting to our perception the deviations from normality (Barlow, 1990).

Associative theories. There is a similarity between a contingent aftereffect and a conditioned response (Harris, 1980; Murch, 1976). Taking the ME as an example, the orientation of the grid is the conditioned stimulus (CS), the colour is the unconditioned stimulus (UCS), and the response to the colour is the unconditioned response (UCR). The contingency of CS and UCS generates a conditioned response, that is, a response to the colour is evoked by the grid. In this sense the aftereffect is present because of a new learned association (Siegel & Allan, 1992; Siegel, Allan, & Eissenberg, 1992; but for a critique, see Skowbo, 1984). In the ME, after being exposed to red horizontal bars, people look at gray horizontal bars and see them as greenish. What is associated therefore is not horizontal and red but horizontal and a negative response to the perception of red, an unconditional neutralizing response (Harris, 1980). This neutralizing response is the same as that responsible for negative colour aftereffects.

Colour aftereffects have been made contingent on several kinds of spatial patterns, and on motion (Durgin, 1996; Harris, 1980). Motion aftereffects have been made contingent on colour, texture, depth, and even direction of gaze (Mayhew, 1973). This supports the associative theory, because CS and UCS can belong to almost any stimulus dimension, and be associated only on the basis of their spatiotemporal contingency.

It may be that more than one mechanism is responsible for different aftereffects. Bonnet et al. (1984) for example, distinguish between an immediate noncontingent motion aftereffect that is explained by sensory adaptation, and a residual contingent motion aftereffect that is explained by an associative conditioning process (see also Favreau, 1976, 1981).

An in-depth discussion of the relative strength of the theories of contingent aftereffects is outside the scope of this paper. What is relevant for an understanding of the detection of displacement data is the following: (1) The effect of adaptation can be long lasting and can be eliminated by extinction trials; (2) the effect is contingent on many stimulus dimensions; (3) there is no necessity of double-duty neurones for every contingent aftereffect observed.

Some remaining issues about adaptation

A problem with the idea of adaptation is that a probe is not the only way to find the distortions related to representational momentum. For example, in Hubbard and Bharucha's experiments a probe was not used, instead the observer was asked to indicate the vanishing position of the object with the pointer of a mouse (Hubbard & Bharucha, 1988). Their results do not conform to the idea of an displacement aftereffect, because the mouse is quite different from the object. They also report that cognitive expectations, like the knowledge that the object will bounce from a wall, affect the judged vanishing point. Perhaps an expectation effect may exist on top of the adaptation effect, and may be related to the effect of knowledge discussed earlier (Ball & Sekuler, 1980). As mentioned earlier, eye movements may also have played a role in these experiments.

Hubbard (1993) also found that a larger rectangular frame around an object that is rotating affects the representational momentum of that object. If the context moves in the same direction the effect increases, if it moves in the opposite direction the effect decreases or disappears. This, at least in part, can be due to relative displacement of the probe orientation with respect to the context orientation. Interestingly, Hubbard (1993) found no significant distortion when the context was absent, and he attributes this result to the fact that, unlike his experiments, in most representational momentum experiments direction of motion is a between-subjects variable. This fact would be expected on the basis of a perceptual adaptation process. In the condition where no context is present the limited strength of the induction stimulus is cancelled by the presentation of trials with motion in the opposite direction. These trials have the effect of extinction trials (see Kerzel, this issue, for related findings).

In static displays where there is no inducing motion, there is a learned contingency of the displacement with a particular stimulus configuration (for example that of an object falling). Using static displays researchers observe a bias of the system that is the result of a contingency learned outside the laboratory. This is an interesting condition because it may be a boundary situation between purely perceptual calibration and abstract learning. The diverse past experiences that contribute to the effect have a very abstract common feature, thus if this kind of learning actually takes place the best term to describe it is abstraction (see Gibson, 1969, for a description of abstraction as the mechanism of perceptual learning).

Considering that contingent aftereffects can be long lasting compared to the short adaptation time necessary to induce them (e.g., Jones & Holding, 1975), and that after an initial exponential decline the decay function is almost flat (Bonnet et al., 1984), the sensory adaptation explanation can be stretched to explain the available data, but probably the best explanation is not sensory adaptation but perceptual adaptation, in the sense of a quick priming effect that produces motion (or displacement) contrast (Raymond, 2000; Raymond et al., 1998). In this case one also needs to assume the existence of priming effects by a context and not just by the displacement itself.

CONCLUSIONS

In this paper I explored the possibility that a known phenomenon that has been explained by assuming a representation of forces can be described as the outcome of a particular kind of perceptual adaptation. I have paid attention in particular to the use of the concept of internalized dynamics, and its limitations. I hope that I have given space to both the pros and cons of the alternative explanations.

Let us consider what the process of adaptation suggests about several aspects of the problem: (1) Representational momentum can be described (explained) as a change in the representation or as a result of a change in sensitivity to displacement due to sensory or perceptual adaptation; (2) as described earlier, representational momentum is consistent with the pattern of motion (Verfaillie & d'Ydewalle, 1991, call it the "higher-order event structure"). This is the pattern of motion presented during adaptation; (3) it has been reported that representational momentum is reduced by using different directions within the same experiment (Hubbard, 1993; Kerzel, this issue). This is not easily accounted for by any theory in the literature. Adaptation can take place within a trial, but it is also possible that exposure to the opposite transformation of the same object will decrease the effect, because these trials in the opposite direction have the effect of extinction trials; (4) representational momentum is contingent on shape of the object (Kelly & Freyd, 1987). In terms of adaptation the effect is contingent on shape, and other aspects of the display; (5) the parallel with the physical laws of motion need not be perfect; (6) using static displays a bias in detection of displacement is found when previous experience has been associated with a direction of motion. Detection of displacement for a person jumping from a wall is biased because only (mostly) downward motions of that object in that context have been experienced before. Experience of similar objects moving downward in similar contexts can by itself produce the distortion because of generalization of the effect. Alternatively, instead of contingent sensory adaptation, one could describe the context as providing a priming that shifts visual attention and leads to motion contrast (Raymond et al., 1998). This is the difference between sensory and perceptual adaptation discussed earlier in the paper.

Having said all this about the characteristics of adaptation it is fair to ask how to discriminate empirically between this and the explanation based on dynamic representation. Can a change in sensitivity or a visual selection contrast effect be merely other names for a change in the dynamic representation? New empirical research is necessary especially with respect to the number of aspects of the display that can be made contingent on direction of motion and therefore produce memory distortion (errors in detection of displacement). The difference between the two ideas can be rephrased in the following way. According to the dynamic representation model the transformation presented (or suggested) is used as a predictor of the future evolution of the event. Therefore the system guesses something about the distal object, such as its future position, based on ecologically valid laws. On the other hand, according to the adaptation idea, a presented transformation produces a neutralizing response. This effect decays rapidly initially, but, in absence of stimulation, does not disappear completely for many seconds. The neutralizing response is associated with the context and can be observed later under appropriate conditions.

Often the choice between two theoretical models is not based on finding a critical experiment that rules out one of the two. In the absence of a final experiment, other considerations are important: On the one hand Freyd's theory (1992) has the advantage that it seems to address more directly the question "why", i.e., the functional nature of the effect. Hubbard's theory (1999) probably accounts for more data than any other theory, but at the cost of assuming many internalized invariants. On the other hand, the perceptual adaptation explanation has the advantage that it places this displacement effect together with a large number of other well-documented phenomena. I hasten to stress that in no way I am suggesting that representational momentum is as simple as an aftereffect, rather adaptation effects are starting to be recognized to be as complex as representational momentum.

The dichotomy between processes that are hard-wired in the human brain and processes that are similar to reasoning can be a misleading way of conceptualizing human perception. Just as primitive humans used to think about the sun as a living organism, early psychologists thought that perception was but unconscious thinking. This view has been refined but the starting point is still the parallel between solving the ambiguities of the stimulus and pursuing a scientific goal, or maybe solving a puzzle from a magazine (Rock, 1983). In opposition to this view, the Gestalt theory stressed the existence of universal laws of perception. Both positions tend to overlook the plasticity that is specific to the perceptual system. Perceptual learning and adaptation through experience need not be similar to conceptual learning. The first author to take this position to my knowledge was Eleanor Gibson (1969). She stressed that perception is always active and in this sense different from the old idea of Pavlovian conditioning during which the animal is passive. As Konrad Lorenz pointed out in 1965 even the simplest form of associative learning requires a neural substrate that makes learning possible, and every form of associative learning has to be cast within the context of the general pattern of behaviour of the animal. These ideas have been integrated in the modern theories of conditioning (Rescorla, 1988). Capitalizing on this more sophisticated view of conditioning and learning, researchers are trying to explain perceptual phenomena such as aftereffects based on something not too dissimilar from conditioning (Siegel & Allan, 1992). With respect to adaptation to motion, a recent important contribution is the discovery that under some circumstances adaptation requires attention (Raymond et al., 1998).

Much work is necessary to understand adaptation to change well enough to say something conclusive; however, for a system that is meant to detect change, it is important to adjust to patterns in the stimulation. I believe I am here joining the voice of most researchers working on sensory and perceptual adaptation (e.g., Barlow, 1990) in suggesting that distortions of memory for position as well as aftereffects and priming are not simple curiosities, nor are they by-products of a biological limitation, they are part of the very basic structure of the perceptual system.

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