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The Failings of Three Event Perception Theories

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INTRODUCTION

Unlike in other domains of psychology, empirical research on event perception is dissociated from its theory, maybe because both lack definition. In this paper I attempt to bring the two together. Perceptual events refer to moving objects that are part of an action. The breaking of glass, the launching of a cannon ball, etc. are events. Dynamic attributes of events cannot be reduced to shape and position but involve such complex features as mass, energy, or friction. Colliding objects, the change of the water-level in a tub once an object is submerged, etc. are examples for events. According to Gibson (1979) they consist of reversible events (the bounce of a ball) and irreversible events (shattering of a glass). He grouped events into rigid object displacements, collisions, non-rigid object deformations, surface disruptions, and surface deformations. This characterization emphasizes the importance of naturally occurring terrestrial events for human perception. Event structures are nested patterns in space and time that provide the basis for coordination between stimulus and action (see also Flach, Lintern & Larish, 1990). Fowler and Turvey (1978) extended the notion of event and defined it to be the minimal system—consisting of the actor and her environment—that will adequately describe skilled performance.

When asked to throw a ball, say a baseball, as far as possible, many people will propel the ball at a launch angle that is much too shallow (Krist, 1992). However, with a little practice, they will unknowingly home in on a strategy that is optimal, that is they will come close to a launch angle of 45° (Stimpel, 1933). This example betrays poor conceptual knowledge and equally poor implicit action knowledge. It also shows that implicit knowledge is quickly adaptable to the required task. The tuning of the system to the appropriate parameters that allow one to throw the ball the farthest with the least effort must have been informed by perceptual information about the success. When taking a closer look at the perceptual competencies that play a role in these and other complex events, one body of literature finds that observers are rather capable (e.g. when judging the arrival-time of an approaching target on collision course, Lee, 1976; Peper, Bootsma, Mestre, & Bakker, 1994) while another finds that many systematic errors are made (e.g. DeLucia & Warren, 1994; Kerzel, Hecht & Kim, 1999).

I will argue that such contradictions do not reflect exceptional cases but are typical for the field of event perception. They point to an inadequacy of current research, which fails to test and possibly falsify existing theories. To prepare the argument, I first characterize our thinking about events and the problems associated with it. Then, drawing on research in the domains of space perception, arrival-time estimation, and conceptual understanding of events, I describe examples of problematic or misguided research. I show that event perception research—in contrast to the theories—relies on highly problematic implicit assumptions. Finally, I outline a number of solutions to this problem.

CURRENT RESEARCH DOMAINS OF EVENT PERCEPTION

The existing research on events can be loosely grouped into three domains. I chose the domains based on the three theoretical approaches that seem relevant: direct perception, inference theory, and internalization.

The failings of direct perception

In a phenomenological sense it is true that we have immediate experiences of complex impressions such as intention (Heider & Simmel, 1944) when viewing moving geometrical shapes. Michotte (1946) reported that, when shown synchronized approach and separation of line segments, observers reported strong impressions of causality that were as compelling and immediate as other sensations. In a similar vein, Johansson (1950) demonstrated that specific acceleration patterns of point-lights are readily seen as human figures. And Gibson (1979) claimed that perception of dynamic qualities such as weight, force, causality are given in a direct manner by virtue of invariants in the optic array that uniquely specify such events. Ecological psychology deserves credit for emphasizing this event character of perception. However, the notion of direct perception is too vague to be tested empirically although it can and has been criticized (e.g. Ullman, 1980; Fodor and Pylyshyn, 1981). I focus on the principle of kinematic specification of dynamics (KSD) and on tau theory to demonstrate the lack of development in this domain.

KSD states that direct perceptual qualities emerge when the dynamics of a situation is sufficiently specified by its kinematics (Runeson, 1977; Runeson & Frykholm, 1983). For example, in the case of two colliding billiard balls, the specific velocity changes of incoming and exiting balls can only be obtained with one particular mass ratio. KSD claims that people perceive the mass ratio directly based on the kinematics of the event (i.e. changes in the velocity vectors between pre- and post-collision phases). Unfortunately, the KSD principle in its strict form has met with sufficient counter-evidence such that it should be considered as falsified. In its weak form, stating that dynamic judgments can be based on incomplete invariant information, the principle cannot be falsified (Hecht, 1996). It is thus mandatory, that empirical research on events from an ecological perspective states testable hypotheses that can be derived from or inspired by direct perception.

The second prime example for direct perception is tau-theory, which postulates that time-to-arrival judgments of oncoming objects are based on the rate of relative optical image expansion (Hoyle, 1957). Tau-theory may well be the best researched domain in all of event perception (Lee, 1976; for an overview see Tresilian, 1991, 1994). However, despite the vast amount of research conclusions are contradictory and often paradoxical. Evidence is accumulating that not tau but other simpler variables are used by observers to make arrival-time judgments (Heuer, 1993; Kerzel, Hecht & Kim, 1999; Smeets, Brenner, Trébuchet, & Mestre, 1996; Smith, Flach, Stanard & Dittman, 1998). Nonetheless, tau theorists fail to concede that tau does not always work. Tau theory is lacking specific predictions that specify when people use which tau parameter. Although direct perceptionists have drawn our attention to the complex functioning of perception-action processes in other domains (e.g. Heft's, 1993, studies on reachability judgments), the tau community does not seem to realize the evidence against tau. To the contrary, unexplained empirical data have prompted researchers to investigate the coupling between two tau parameters (Grealy, 1997).

The failings of direct perception thus lie in the failure to reconcile the conflicting results within the relevant sub-theories. The general theory is difficult if not impossible to evaluate because many researchers do not explicitly derive their claims from it but are only known to be direct perceptionists because they come from a Gibsonian background.

The failings of inference theory

Inference theory states that we perceive objects through a process of inference, inverse optics, or reconstruction that is based on insufficient retinal evidence (Al-Haytham, 1034; Helmholtz, 1867, 1894; Poggio, 1990; Poggio, Torre & Koch, 1985). Helmholtz conceived of inference as an inductive process that derives general rules from a few contiguous co-occurrences of events. Such unconscious inferences require a causality principle. Inference theory has received strong support ever since (e.g. Rock, 1983, 1997), but it has not been applied to complex moving stimuli until recently, when the use of heuristical rules of inference has been proposed (Braunstein, 1972; Todd & Warren, 1982). The term heuristic is suggestive of rules being consciously applied by the perceiver or by some homunculus looking at the retinal image, but this is not meant. Perceptual heuristics (PH) are usually not available to introspection.

This notion of heuristical inference was applied to dynamic events in the context of planar collisions (Gilden, 1991; Gilden and Proffitt, 1989; Proffitt & Gilden, 1989; Proffitt & Kaiser, 1995). Gilden and Proffitt posit that in the case of two colliding objects, such as two air hockey pucks, observers base their judgments on simple heuristics (e.g. "the puck that exits fastest after collision is lighter than the slower object"). The supporting evidence that observers might take a reduced aspect of the kinematic information that is available to them and apply an over-simplified heuristic to it comes from a bimodal distribution of responses (Gilden & Proffitt, 1994; but see also Runeson, 1995), which is incompatible with the continuous relationship between the respective ratios of masses and exit angles of the colliding objects. Unfortunately, this notion of perceptual heuristics is too vague to derive any falsifiable statements (Hecht, 1996). Moreover, the perceptual heuristics approach suggested by Gilden and Proffitt is unable to explain the remarkable performance of experts, which would require a large and rather sophisticated set of heuristics.

A somewhat different sort of inference, according to Braunstein (1994), is assumed in the notion of a decoding principle, which was first suggested by Johansson (1977) and formalized within a Bayesian framework by Bennett, Hoffman & Prakash (1989). Braunstein argues that a decoding principle constitutes inductive reasoning because conclusions (e.g. the 3-D interpretation of a perspective drawing) are drawn that go beyond the stimulus and require some additional assumptions (e.g. a rigidity assumption). From an indirect perspective of perception it is impossible to refute the notion of inductive inference, since this would be tantamount to denying the underspecification problem and acknowledging that the percept can be deduced unambiguously from the retinal information. However, ambiguous figures demonstrate that inferences are not necessarily stable and their premises subject to spontaneous change.

In sum, the following picture emerges for inference theory. (1) If one refutes the notion of direct perception, inference of some sort seems to be required to bridge the gap between stimulus and percept. (2) The notion of inference suggests thought-like albeit unconscious processes of visual problem solving. The claim that there is a language of vision, which would justify the choice of the term heuristic, has not been made explicit. A theory of visual inferencing rules is lacking. (3) Modern inference theorists have not yet spelled out any specific inferencing rules. They even seem to be more cautious than Helmholtz and avoid specifying whether these rules are inductive or deductive. And it may be impossible to determine experimentally whether the visual system induces, that is generalizes, from a few past cases to a new stimulus interpretation, or whether it relies on additional assumptions that allow deducing the interpretation that is perceived. (4) The attempt to spell out inference in terms of perceptual heuristics by Proffitt and Gilden is not falsifiable unless hypotheses are added that specify what heuristics come to bear under which circumstances.

The failings of internalized constraints

The third and last approach to event perception tries to avoid committing to a direct or indirect view. Whether the visual system infers the correct solution or whether it is attuned to an optical invariant, it is still possible to describe a set of rules that constrain the search space under normal circumstances. According to Shepard (1984, 1994), such rules can be found in constraints that were immutable in our environment, such as light coming from above, or the circadian rhythm of light and dark. Such constraints, Shepard continues to argue, have been internalized by the organism through evolution. Presumably, this could be done in the hardware of the system, in which case direct perceptionists would be pleased. For instance, a speedometer or a polar planimeter reflects constraints by which it relays distance or velocity information without having any knowledge of these dimensions (see Runeson, 1977).

Interpreted in an indirect fashion, this could also be done by internalized heuristic knowledge that constrains the decoding of the visual stimulus. Internalization theory wisely leaves open the question of whether the visual system infers, thinks, or just processes. The theory is content with predicting perceptual preferences from regularities that have been prevalent in the physical world for long enough to have been internalized by the visual system. For instance, Proffitt and Kaiser (1998) utilize the concept of internalization to argue for abstract heuristics. They suggest that the visual system has not internalized dynamic constraints but rather geometric concepts.

Thus, the strength of internalization theory lies in its descriptive nature. However, to be of predictive value it also has to state how a constraint affects perceptual processing. To set itself apart from other (not internalized) constraints, the internalizationist has to add under what circumstances a regularity in the world becomes internalized. Shepard (1984) states that the constraining power of the internalized regularity becomes visible whenever the percept is underspecified, such as in imagery or apparent motion, but apart from examples, he does not specify a list of regularities that could be tested empirically. The few examples that have been put to empirical test do not speak in favor of Shepard's ideas. To support this claim, we need to provide a fair test of the internalization hypothesis, which would have to cover different levels of analysis that range from implicit, even hard-wired constraints to more or less explicit constraints, which may still be reflected in our cognitive understanding of physical events (Hecht, in press).

Shepard's own example of kinematic geometry constraining apparent motion is farthest removed from cognition. It has met with severe criticism (Todorović, 1996; see also Hecht & Proffitt, 1991) and thus lost its persuasive power. Another elegant candidate for the internalization of a regularity has been suggested with gravitational acceleration disambiguating absolute size and distance (Watson, Banks, von Hofsten, & Royden, 1992). Knowledge about the gravitational constancy is technically sufficient to calculate absolute size of an unfamiliar object that is falling at an unknown distance from the observer. If it is falling from rest, neglecting air resistance, it will take approximately half a second to fall a distance of 2 m. Once the absolute size is known, absolute distance is derivable from the size of the retinal image. The same reasoning can be applied to objects that do not start from rest. If the gravitational constant has been internalized, observers should be able to make rather accurate distance and size judgments of such unfamiliar objects. Unfortunately, this is not the case. Judgments reflect some knowledge that fast moving objects are closer to the observer than slow objects, but beyond this observers were not sensitive to acceleration (Hecht, Kaiser, & Banks, 1996).

One might argue that internalized regularities are not necessarily applicable to such basic perceptual processes as size and distance perception. Some cognitive processing might be required to bring the internalization effects to the fore. On the other hand, we may be too far removed from specific visual information when we are asked to merely reason about physical events. In addition to reducing the range of permissible areas of investigation to special limiting cases such as dreams or apparent motion we can compare perceptual and conceptual biases to assess the validity of the internalization idea. The domain of naive or intuitive physics (for an overview see Smith & Casati, 1994) lends itself here, and I focus on the understanding of ballistic projectile motion and of horizontality. I chose these examples because in both cases perceptual errors correspond to errors made when reasoning about these cases. Thus, perceptual and cognitive interpretations of the internalization concept are covered.

First, when asked explicitly about the trajectory of a flying cannon ball or of a baseball pitch, or when confronted with animated versions of such events, observers show equally poor understanding (Hecht & Bertamini, in press). They believe that a baseball thrown at a shallow angle will continue to accelerate after it has left the pitcher's hand. Likewise, animated impossible events of the same nature look as natural as do canonical pitches.

Second, children and also many adults fail to appreciate that a water surface of a liquid-filled glass remains invariably horizontal (for an overview of the Piagetian water-level task see Liben, 1991). Many adult observers who are presented with a side-view drawing of a tilted beaker and who are asked to indicate the water surface (if half filled with water), mistakenly draw tilted surfaces. They behave is if they thought the water would rotate together with the beaker when the latter is tilted. When pictures are doctored to show glasses with non-horizontal water levels, these are accepted as natural looking cases (e.g. Howard, 1978). In contrast, an object suspended at and free to pivot around its center of gravity is mistakenly thought to always assume a horizontal position (Roncato & Rumiati, 1986). Thus, we have the paradoxical situation that sometimes participants rely on the horizontality regularity when they should not, and sometimes they fail to rely on it when they should.

This brings us to two important problems associated with the notion of regularity. First, regularities do not exist in any absolute sense but have to be rendered plausible by normal viewing situations and normal context information. The light-comes-from-above regularity stops to be one if we stand on our heads, the circadian rhythm ceases to be observable when we enter a cave. Second, a small change in the level of analysis or scope of a regularity can change its definition completely. Horizontality is a perfect regularity at the level of motionless contained water but ceases to be so in the process of drinking or when considering a seesaw. Given these problems, we may be confined to a serious circularity: it may not be possible to define a regularity independently of the context that is used for its empirical test. Consequently, the notion of internalization ceases to be useful, at least in the context of its more cognitive interpretation.

To summarize, (1) the notion of internalized regularities as guiding principles of perception has intriguing advantages over direct and indirect theories of perception. It could explain how percepts are specified at the unconscious and conscious level without unnecessarily committing to a problematic theory of perception. (2) Those regularities suggested by Shepard and others that could fit the description lack empirical support and/or suffer from a circularity problem. This holds for regularities in the pre-cognitive sense of smart perceptual devices that could reflect the inner structure of the visual system. It also holds for regularities at the cognitive level in the domain of native physics.

Taken together, research designed on the basis of all three approaches runs into serious empirical trouble that is not merely a matter of fine-tuning the theories. Also, adding fuzzy operators or probability functions to the existing theories cannot explain the large variances and deviations in the data.

TWO OVERSIGHTS THAT CHARACTERIZE CURRENT RESEARCH ON EVENT PERCEPTION

Let us take a step back and attempt to find similarities between the three approaches that might explain their relative inadequacy. Once I have identified some of them, I will outline solutions. All three approaches to event perception have neglected the role of meaning and relied too heavily on pictures. Ecological perception has failed to reach its own goals while inference theory and internalization do not provide for eventhood by virtue of their theoretical makeup.

Neglecting intentionality

The three approaches to event perception deal very differently with the problem of intentionality. Within *direct perception*, Gibson's (1966, 1979) concept of affordance does quite explicitly posit that perception is inextricably tied to meaning. Gibson introduced the concept to bridge the gap between environment and observer. He claims that we do not primarily perceive attributes or qualia of objects but their uses. "The meaning is observed before the substance and surface, the color and form, are seen as such." (Gibson, 1979, p. 134). And this meaning is invariantly present in the object regardless of our momentary needs. The step from meaning to intention appears to be a major obstacle for direct perceptionists. For instance, Ginsburg (1990) believes that intentional states are incompatible with the notion of affordance. Such strict interpretations of Gibson's realism may be responsible for the failure to take the step. Meaning is a necessary but not sufficient condition for intention. The observer has to select among the indefinite number of meanings. Heft (1989) has attempted to bridge this gap by arguing that intentions are action possibilities.

With few exceptions (e.g. Bingham & Muchisky, 1995) followers of Gibson have shunned the concept of intention rather than making it the corner-stone of research on event perception. Tau-theory assumes that if the invariant tau that specifies arrival-time is present in an abstract informational sense, it can and will be used by the visual system. Selecting among affordances according to situational needs has never been made an integrative part of tau-theory. The only step in this direction, Tresilian's (1995) notion of cognitive processing, is a modification of tau estimates rather than an affordance-based evaluation of information pick-up. However, we undoubtedly perceive an object on collision course quite differently depending on our intention to catch or our concern not to be hit by it.

Researchers who directly investigated affordances, have understandably focused on cases where the meaning of the stimulus was unambiguous, in the sense that observers had to fulfill one well-defined task, such as passing through an aperture while carrying a large object or climbing stairs (Warren, 1984). Not so in simulated approach scenarios, where we find performance data that vary considerably across paradigms (see Tresilian, 1991). I suggest that rather than singling out some situations as ecological and others as unecological because they involve allegedly strange viewing situations or simulations (e.g. Michaels & Carello, 1981), observers' intentions in these experiments should be systematically investigated. This can shed light on such findings as the result that the invariant information necessary to catch a fly-ball only seems to be processed when observers are in the field attempting to catch it (Oudejans, Michaels, Bakker & Dolne, 1996). Similarly, the principle of KSD (Runeson & Frykholm, 1983) has been explicitly developed within the direct approach to perception and assumes a more or less automatic pick-up of information once it is specified by the visual kinematics. Intention is not considered and contradictory evidence obtained in cases where observers do not seem to extract dynamic properties from kinematic displays, is explained by the incompleteness of some invariants (Runeson, 1989).

Thus, the notion of intention and situated action as part and parcel of perception has not found its way into current "Gibsonian" research of event perception. Instead, stimulus-based processing hypotheses are favored once the relevant dynamics are sufficiently specified by the kinematics.

The picture for *inference theory* looks even more disappointing. Computational perceptual theories have come to realize that Marr's (1982) bottom-up approach is not able to fully account for the recovery of 3-D object structure, and they have proposed active purposeful vision to provide the missing information (Aloimonos, 1993). However, in the domain of event perception such a notion has not been entertained. Inference theory neither claims that inferences are inductive, which would have put it in a class with Marr's approach, nor does it explicitly call for an incorporation of top-down processes and meaning. Given the cognitivist structure of the inference theoretic background upon which the PH approach is based, it could easily be changed to incorporate the purposive structure of behavior. Not only would such an incorporation be possible, it could serve as a rationale for adding the missing hypotheses about what heuristic is used under which circumstances (see section "the failing of inference theory" above). While PH theory presently allows the prediction of bimodal judgment distributions on the basis of a change of heuristic, it has to rely on a circular argument to explain why such a change occurs. Perceptual salience is thought to select the heuristic that becomes active, and the activation of this very heuristic then is taken to explain the perceptual outcome.

By including intention into this scheme, we can resolve the circularity problem. As an example of how this can be done, let us reconsider the water-level problem. In PH language, observers fail to apply the horizontality heuristic to this task. An analysis of intention predicts that actions depending on this knowledge correlate with accurate use of the horizontality heuristic, while actions for which this knowledge is distracting prevent the heuristic from being applied. And indeed, expert glass handlers, such as waitresses, experience an even lager bias (Hecht & Proffitt, 1995; but see Vasta, Rosenberg, Knott & Gaze, 1997). The purpose of not spilling the liquid inhibits the horizontality heuristic and activates another that consists in keeping the liquid surface as far beneath the lip of the container as possible to prevent spilling. In this example, the role of intention is not situation-specific but rather has become part and parcel of the skill that makes an expert waitress. Hence it is possible to investigate intention without having to induce it in a particular situation or having to communicate it to the observer via instruction. The study of experts thus provides another experimental handle on task-dependent perception.

The approach of *internalized constraints* is harder to judge with respect to the role of intention, but it seems to be twice removed from action goals. First, an internalized constraint by definition transcends specific situational needs as it serves to disambiguate perceptual information. A given constraint (e.g. minimal circular geodesic motion paths) has to be applicable to perception, imagery, and dreaming (Shepard, 1984) since it is a default rule. Second, the processes of internalization requires relative constancy of the organism's need and the respective environmental layout. Color constancy could not have developed in a world where objects continuously change their reflectance functions, but it could also not have developed in a world where color has no vital significance, such as red indicating ripeness of a fruit. Thus, the idea of internalization focuses on constancies that remain once situational aspects are removed.

Interestingly, Gibson (1979, p. 18) makes a very similar point, arguing that affordances of the environment, such as an up-down reference given by gravity, have been invariant throughout evolution. In this sense his position might be compatible with Shepard's. When we perceive in a direct fashion whether a surface is sit-uponable, we rely on the gravitational reference to establish that we will not immediately slide down from it because of its tilt. However, deviating from Shepard, Gibson's notion of affordance also incorporates meaning.

In sum, the advantage of incorporating intention into the research questions of all three approaches is quite obvious. It has been suggested in other domains (Ach, 1905, 1935; Allport, 1987; Hommel, Müsseler, Külpe, 1893; Neumann & Prinz, 1987; Prinz, 1987, 1998) but has thus far not been exploited for event perception.

The percept continues to be mistaken for a picture

The reason for this deficit could lie in the resilient camera metaphor. Two assumptions can describe the constraints that it exerts, the myth that the percept is a reconstruction of the distal object and the assumption of monocausality of a front-end that works like a camera. According to this metaphor, the percept is insufficiently specified by the retinal image (Poggio, 1990) and thus has to be reconstructed. This reconstructionist view continues to guide current theorizing about perceptual inference although traditionally the percept was not understood as a picture but rather as a sign or a symbol that stands for objects and events in the world (Helmholtz, 1867; Brunswik, 1955; see also Mausfeld, 1994). For instance, Hoffman (1998) considers the fundamental problem of vision to be the indefinite number of possible interpretations for the proximal image. He presupposes that perception is like reconstructing a 3-D scene from a 2-D image. Moreover, he assumes that the visual system (re)constructs the perceived world by means of general rules, be they heuristics, Bayesian inference rules, or system constraints. Hoffman (1998, p. 27, p. 165) identifies 35 such rules ranging from mapping rules ("Always interpret a straight line in an image as straight line in 3-D") to assumptions about the world ("Light sources move slowly"). As intriguing as such a collection of rules may be, it is not suited for event perception because it interprets too narrowly the relation between proximal stimulus and percept.

The situational context of the perceiving organism should not be treated as noise but rather as important variance in need of explanation. Outside the domain of event perception there is ample evidence for the importance of situational variables. Typical findings are that intentions and/or actions facilitate percepts to which they are similar. For instance, intention can change spatial compatibility effects (e.g. Hommel, 1993; but see also Müsseler & Hommel, 1997), and the directionality of ambiguous apparent motion can be determined by the direction of a concurrently executed hand movement (Shimojo, Tanaka, Hikosaka, & Miyauchi, 1996). Similar effects are commonplace in the domain of attention research and motor expertise.

For most of the examples evoked in the section on current research domains, the reconstructionist view seems to have underlain the experimental rationale. For instance, reconsider the case of colliding air hockey pucks. According to PH the percept "light" is constructed from the relative velocity in the proximal stimulus together with the heuristic that the faster object is always lighter. Assuming internalized knowledge of the sort that light objects have less inertia and generally move faster, the internalization approach comes to the same conclusion. The principle of KSD claims that the velocity ratios per se specify the relative weights and thus no inferencing rule is needed. Be this as it may, in all cases researchers have attempted to explain the percept based on the implicit assumption that it directly or indirectly reflects the distal object. The weight ratio of the colliding pucks is obtained through reconstruction. This is the camera metaphor of visual perception. The presumed task of the visual system is reduced to gleaning a 3-D interpretation from the proximal stimulus.

One important fallacy that results from the camera metaphor is the belief that the same stimulus is always processed in the same manner. PH, KSD, and internalization do not make predictions that differ as a function of the state of the organism. Top-down processes, such as involved in reversals of ambiguous figures (Rock, 1983), are considered problematic but rare exceptions and do thus not feature in event perception theories.

Our initial example of time-to-contact judgment is more complicated since researchers assess perceptual experience indirectly by means of timing judgements. Tau-theory neither explains percepts nor does it require a conscious percept to explain behavior. The theory predicts how visual information functionally guides action. Only in this basic sense can TTC be said to be "perceived". The camera metaphor is thus less likely to misguide the researcher who employs arrival-time judgements. However, the desire to produce a single solution to any given visual approach scenario, the reliance on purely optical analysis without regarding competing interpretations, still reflects the camera metaphor to some degree. Gibson's realist position may not acknowledge the underspecification problem or may consider it solved by the extraction of invariants, but also relies on camera-like seeing with the emphasis on ecological optics. He has not spelled out under what circumstances a single optical array leads to the perception of multiple affordances. Neither does the promising invariant of tau allow multiple percepts. The optical information may be identical while the anticipated action is very different. In catching we need rather precise information about position and timing, in avoiding the ball we can leisurely err on the safe side and move to soon or more than required by a near miss. If we assume that the varying precision required by anticipated actions is the rule rather than the exception, would not the premises of our conceptual thinking of perception change?

In sum, I speculate that research on visual event perception has not addressed these issues because it is still trapped in the camera metaphor, which suggests a direct mapping between stimulus and percept, and which follows a fixed set of immutable rules. We need an alternative that explains the changing solutions as a function of the task with which the visual system is confronted. The next section considers paradigms that might hold solutions for these shortcomings, such as an evolutionary notion of adaptation.

SEARCHING FOR SOLUTIONS

Perceptual categories need to be supplemented with meaning, purpose and appraisal

In addition to the effects of intention, I contend that the percept is also influenced by the perceiver's appraisal of the action after it has been carried out. The success or failure of an action influences how it is perceived by the actor. While Thorndike (1898) established that the success or effect of an action influences its memorability in a lawful fashion, theories of perception have not formulated a similar law of effect, maybe with the exception of Gestalt psychology (see e.g. Koffka, 1935). But Gestalt scholars have not made such effects the object of systematic empirical work. Within the domain of event perception the recent progress of computers and animation software certainly puts us in a position to test this idea experimentally. First studies that used a simulated squash game (Hecht, 1997) produced promising results. Observers had the task to hit (via mouse action) an oncoming squash ball. Their racket was invisible and could be changed in size such that identical events and hitting actions sometimes produced successful hits and sometimes misses. When observers judged the veridicality of the simulation, which could also contain physical anomalies, the success of the action strongly influenced their judgments. Successful trials were judged to be more realistic than unsuccessful ones. We should thus consider supplementing our language of perceptual theory with additional categories or even parse the research areas in very different ways. One parsing along these lines might be to distinguish perception of edibility, animacy perception, manipulability, failure, etc.

If taken seriously, the incorporation of purpose and appraisal not only suggests that we perceive the causal relationships in collisions or in ballistic motion (see above), but that we also perceive them differently as a function of our intentions. For example, the speed and position of a billiard ball should be perceived differently when observing someone else or when pocketing our own ball. The same objective movement is perceptually different depending on whether the ball is (taken to be) deliberately struck by the cue-ball or if it inadvertently collides with another ball on the table. This does not necessarily mean that the observer has to represent action goals explicitly. An expert chess player, for instance does not "think" about her next move but intuitively executes it, even while performing a secondary task and under time pressure (Gruber & Strube, 1989; Dreyfus, 1996). Moreover, the sequence of the moves appears planned and strategically premeditated. Likewise, the expert tennis player neither experiences the intention to return the ball nor has the time to anticipate it in thought. It is quite conceivable to have purposeful action without explicit representation. In this sense, intentionality is an aspect of perception (see also Merleau-Ponty's, 1945, notion of action without goals that accompanies perceptual-motor skill). The study of expert performance in this context is mandatory as it allows to observe the transition from premeditated purposeful perception to automated action.

Perceptual processes obey satisficing rules

As another instance of the camera metaphor, perceptual theories tend to formulate laws about mapping relations between the stimulus and the percept. With the exception of Gestalt theorists who indulged in pointing out competing principles of perceptual organization, conflicting laws within the same theory are usually considered to be problematic. The seemingly contradictory empirical evidence can be reconciled in a theory of event perception that deliberately features conflicting mechanisms together with statements about the circumstances under which they are activated. I further suggest that the visual system is economic in the sense that it chooses the mechanism that suffices to achieve a desired result. If follows satisficing rules. That is, a hypothesis about event perception is not fruitful without specifying the boundary conditions that are determined by the meaning of the perceptual action.

Satisficing principles For an artificial vision system it is computationally prohibitive to search (algorithmically or otherwise) for an optimal solution. We have to settle for an adequate or satisfying solution. Simon (1969, p. 138) called this system property 'satisficing'. His argument is simple and convincing. It rests on two premises. First, a system will not do what it cannot do. Many optimization problems, such as the traveling salesman problem, are so complex that they cannot be solved algorithmically. For example, the task to visit all European capitals in Europe has approximately 10^{81} possible routes, more than there are stars in the universe. To solve the problem of minimizing the total distance traveled, only an approximate solution can be found by a system with finite resources (Eigen, 1998). This also holds for complex events. Only in artificial stationary situations might the percept be described algorithmically as a function of the proximal stimulus. Second, the agent accepts alternatives that are good enough to satisfy his/her needs.

Applied to event perception, satisficing poses the following problem: the visual system has to know what level of detail is required in order to satisfy a given need. Thus, I need to assume that the visual system can choose between different ways of performing. In the case of arrival-time judgment, an approaching object is perceived differently depending on whether it needs to be recognized, caught or avoided, or just judged as to whether it is closer or farther away than another object. Presenting the visual system with a task that it can easily solve, as often demanded by ecological psychologists, may not say anything about its potential. We would have to assess where it breaks down to be sure what information it cannot—under the best circumstances—process.

Satisficing is similar to the notion of heuristic or unconscious inference. It is an anthropomorphic description of what the visual system does. Satisficing is different from inference in that the same premises do not always lead to the same conclusion. The visual system could sometimes rely on a simple perceptual heuristic, while at other times it has to elicit more complex processes. Cognitive, emotional, and motivational states of the observer (Gigerenzer, 1997; Gigerenzer and Goldstein, 1996) can affect the satisficing solution. There is incidental evidence that many social variables can affect visual perception. For instance, the perceived brightness of appetizing objects increases with food deprivation (Gilchrist & Nesberg, 1952). In the same vein, geographical slant was overestimated as a function of physical fatigue (Proffitt, Bhalla, Gossweiler & Midgett, 1995). However, these findings were not predicted by present theories. The challenge in applying the satisficing principle to event perception lies in providing additional theoretical arguments for the prediction of particular perceptual mechanisms and their level of complexity.

A new minimum principle The notion of satisficing is assuming a minimum principle, but it needs to be elaborated. If the visual system always picks a least-effort strategy, we need to evaluate the costs of different perceptual strategies. In the case of global optical flow, Kerzel and Hecht (1997) found heading detection to be consistent with the use of a simple image-based strategy as long as the stimuli allowed its use. Once prevented from using such a strategy by very slow flow fields, observers showed evidence of a more difficult global flow analysis. To make the case for satisficing the cost of comparing image velocities has to be smaller than that of processing global flow. Instructions to explicitly use one or the other strategy or speeded and timed heading judgments can measure these costs.

Existing minimum principles, be it perceptual grouping, coding theory, or minimal apparent motion paths (Restle, 1979), are concerned with the most parsimonious description or interpretation of the proximal stimulus. They remain within the percept. From an evolutionary perspective is it not plausible that the organism has evolved to produce efficient or minimal percepts. Instead, the organism should accomplish visually guided satisficing actions. We need an according minimum principle. A step toward devising such a principle has been taken by Abernethy (1993) with the notion of minimal essential information (MEI), which states that the visual system will always use the least information sufficient to accomplish a given motor task. However, this formulation lacks independent criteria for falsification. Presently, if a task is accomplished successfully, Abernethy concludes that MEI was used. If on the other hand the task is not accomplished incorrect information was used. One of the most pressing research needs is to specify alternatives that predict success and failure independently. Whether given visual information is essential or not depends on its dispensability with respect to the satisficing needs that are prescribed by the observer's action goals.

The demand characteristic of the task is not the only factor that constitutes a satisficing solution. Its upper limits are set by calibration and learning. This makes the interpretation of failure or success of perceptual tasks considerably more difficult. One way to test for available strategies is to train people on various tasks and investigate the switching costs that occur when switching from one strategy to another. Existing studies of reaching can be reinterpreted for this purpose. For instance, a lack of calibration was found and considered to be problematic (Bingham & Pagano, 1998) when observers were instructed to reach to a location in space where a target had been located earlier. The satisficing principle would state where to expect calibration as a function of its necessity to fulfill the task. When the task allows a margin of error, calibration will not occur even if continuous KR (knowledge of results) is given.

This example shows that satisficing is intimately interwoven with issues of learning although they have historically been separate. On the one hand, we lack a perceptual theory of learning, with the notable exception of E.J. Gibson's (1969) theory of perceptual differentiation. On the other hand, we have rather sophisticated theories of motor learning that tend to neglect the dynamic role of perception. For example, Salmoni, Schmidt & Walter (1984) when considering the mechanisms underlying KR, assumed stable percepts. KR is supposed to strengthen the association between sensory qualities of past movements and desired movement outcomes. However, KR is likely to change the ongoing percept of the event as well. The situation is more dynamic than previously thought. The assumption of appraisal as a natural part of perception also renders obsolete the distinction between natural (response produced) feedback and artificial KR or augmented feedback (Guay, Salmoni & McIlwain, 1992).

In sum, the inclusion of satisficing rules requires that we expand and redefine the parameter space for existing event perception paradigms. The potential influences of situational and motivational variables need to be assessed and the observer's intended actions have to be considered.

THE FUTURE OF EVENT PERCEPTION

Despite the failings of all three approaches, direct perception, inference theory, and internalization leave room to accommodate the moderating role of purpose and appraisal in event perception. Furthermore, each approach can be extrapolated to do so by focusing on its particular strengths. In this sense, all three approaches can be renewed. The renewal suggests a incorporation of contextual factors not unlike Bruner's attempt to create a "new look" by investigating social influences on size perception (e.g. Bruner & Goodman, 1947).

The new look of direct perception

The new look expands the concept of affordance. A slightly more simplistic version of Heider and Simmel's (1944) displays, say two dots that dance around one another, could be perceived as two fighting insects or as two meaningless dust particles. According to Gibson (1966, 1979) both are equally specified with respect to the optical information, but we only perceive one depending on our present state and history of personal development. This idea is already present in Wertheimer (1923), who suggested a perceptual grouping principle based on experience and habit. In general, a more developed theory of affordance has a lot in common with Gestalt theory (van Leeuwen & Stins, 1994). The concept of affordance has to be made non-tautological, it has to predict which of the indefinite number of affordances specified is actually perceived. In many ways this is an extreme position and therefore allows for very informative experiments. If a small kinematic motion is in principle sufficient to specify complex affordances, the main explanatory load has to lie in the perceiver. The theory of affordance also has to be supplemented with a theory of action goals, expected success, appraisal of strength, ability, etc. Gibson scholars have done little to do so (but see the notable exception of Heft, 1989) maybe because many take intentionality to be irrelevant or even incompatible with affordance (e.g. Ginsburg, 1990). It is time to make the necessary additions.

The new look of inference theory

Inference theory builds on the principle that the processes of the visual system are structurally similar to thought processes (Rock, 1983). Therefore, perception and other cognitive processes can be described in a common language that makes it easy to relate perceptual and conceptual knowledge. Also, the notion of satisficing is easy to incorporate into an inference logic of perception and provides a means to rid PH of the circularity problem that renders the approach immune to falsification (Hecht, 1996). Surprisingly, these potential strengths have not been exploited within the domain of event perception. The notion of perceptual heuristics (Gilden, 1991) among which the visual system chooses is rudimentary.

A literal interpretation of Simon's (1969, 1982) satisficing principle and its application to PH would take the visual system to function as a entity of bounded rationality. Its rationality is bounded because its capacity limitations create uncertainty about the future and about costs of information acquisition. These two factors limit the extent to which the visual system can be rational about (re)constructing the perceived world. Satisficing solutions are achieved by setting an aspiration level, which is determined by the action goal and the cost of information processing. As a consequence, if the goal is not achieved, the aspiration level and the percept are changed. Perceptual heuristics lend themselves well to describe satisficing rules. They also seem well suited to describe the top-down processes that become necessary to structure sets of rules (for an analysis of the hierarchical structure of event perception see Proffitt, 1993).

An important finding in the PH literature, the notion of reference frame, can be made more precise by pinpointing satisficing rules. In the above-mentioned Piagetian water-level problem, the cost of not attaining the perceptual goal of keeping the liquid in the glass is compared to the respective costs involved in applying the heuristics. The satisficing addition to PH thus decides the unresolved issue how the visual system chooses among competing heuristics. Provided benefits are considered equal, the system chooses the heuristic that involves the lower processing costs. To test this idea, experiments that systematically vary the desirability of keeping the water in the glass should be performed. Presumably, the task to water plants using a bucket of water makes the horizontality heuristic more attractive.

Another advantage of a language of perceptual inference is the isomorphism between the description of action goals, of visual processes, and of the intersubjective world that we perceive (see Klix, 1980). Inference theory thus does not need to worry about the terminological incommensurability of terms regarding locomotion, intention, and appraisal. In this sense, PH is a cognitivist position akin to Hochberg's (1981) more general attempt to establish a cognitive theory of perception.

In sum, inference theory can be supplemented with satisficing rules to evolve from its current rudimentary and unspecific form into a valuable theory. Perceptual heuristics bridge the gap between so-called bottom-up and top-down processes and do justice to the judgmental nature of perception.

The new look of internalization

Shepard's (1984, 1994) notion of common internalized constraints underlying perception and imagery presumably continues to appeal to many researchers because he solves the underspecification problem and draws on the widely accepted theory of evolution to do so. Although Shepard fails to explain apparent motion paths, absolute size perception, and some intuitive physics judgments, his approach can be salvaged with the help of specific hypotheses from evolutionary theory. To indicate how this can be done, I will first outline the basic ideas of evolutionary psychology, which has focused on problem solving rather than on perceptual processes, and then speculate about how it can be used to predict purposeful perception.

Evolutionary epistemology (EE) promises to hold the key to an explanation of what perceptual functions can be expected based on the environment in which we have evolved and how these functions may have developed. The main argument of EE is that perception serves the function to predict the outcome of possible actions (Campbell, 1959, 1974; Lorenz, 1973; Popper, 1972; Riedl, 1975, 1980, 1996). We have evolved to make good predictions, not to gain ontological truths about the world or to experience nice cineastic perceptions (Riedl, 1992). As a consequence of this emphasis on predictability, perception is fundamentally correct (increasingly with adaptation). We cannot be well adapted to an environment about whose structure we are completely misinformed. To make predictions, the organism expects and searches for rules. It is a fallacy to assume that because mutation and selection come about through error and trial our perceptual and cognitive processes also rely on trial and error (Campbell, 1960). To the contrary, the assumption of lawfulness produces such errors as the gambler's fallacy where independent events are taken to be dependent. The biased heuristics discovered by Tversky and Kahneman (1974) and results from intuitive physics fit nicely into this picture.

EE provides us with the rules that we are evolutionarily predisposed to find, and thus predicts perceptual defaults and biases. For example, EE predicts that our perception reflects the goal of the action, provided it is internally consistent with other beliefs. EE predicts generally accurate perception that, if it errs, does so on the side of the action goal. This fits well with the goal-driven mistakes that are made when judging projectile motion (Hecht & Bertamini, in press). In the example of arrival-time judgment, EE would presumably argue as follows: we already find a very sophisticated but dedicated tau processor in pigeons (Wang & Frost, 1992). The contradictory evidence in studies with human observers suggests that the presumed tau processor has been integrated into or replaced by a more flexible and universal system. This system was guided by the need for sophisticated communication mainly with other members of the species.

Another advantage of the evolutinary approach lies in the possibility of applying evolutionary learning theory to event perception. The organism can be described as having internalized meta-rules, such as Lorenz' (1935) innate teachers, or Campbell's (1974) universal knowledge gaining algorithm. In sum, EE could serve as a source of inspiration for a better theory of event perception. It predicts that perception occurs where automatic information processing and action guidance fail on a regular basis and/or require the attention of the general neocortical processor.

CONCLUSION: TOWARD A PRAGMATIC THEORY OF EVENT PERCEPTION

The three approaches, in their new appearance, have more in common than their appreciation of perceptual phenomenology. Each of them emphasizes one important aspect of event perception: the direct pickup of situational affordances, the thought-like top-down processing in the form of perceptual heuristics, and the disambiguation through evolutionarily internalized world constraints. Despite their differences, the approaches fail in similar ways because their predictions are too general and they neglect semantic and pragmatic aspects of perception. Their respective strengths can be combined advantageously. The role of intention, disposition, and situational context have to be included into a new theory of event perception. Moreover, we need to incorporate the appraisal of the action's outcome. All three existing approaches can and should contribute to this endeavor. The concept of affordance has to be extended and sharpened. We have to be aware of the inherent analogy between perception and language, and we need to exploit evolutionary epistemology. This rapprochement of the new direct, indirect, and evolutionary looks is pragmatic in two senses of the word. First, it emphasizes the purposive nature of event perception. Second, it is pragmatic in its dealings with truth. The direct and indirect approach are no longer taken to be contradictory but are reconciled in an eclectic manner.

Future research not only has to document the state-dependence of perception and the relevance of moderating variables, but we also need an independent assessment of action goals and the visual information that would be minimally required to reach the goal. We need to reassess the parametric space, which is expanded by important personal and situational variables. This reassessment spells out for event perception what a recent holistic move (Neisser, 1994; Uttal, 1998) is demanding for cognitive psychology at large, namely that it is impossible to arrive at a complete understanding of the visual system without also understanding action, interpersonal reactivities, and object recognition.

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REFERENCES

Abernethy, B. (1993). Searching for the minimal essential information for skilled perception and action. *Psychological Research* (Special Issue: Motor control and sensory-motor integration), **55**, 131–138.

Ach, N. (1905). *Über die Willenstätigkeit und das Denken.* Göttingen: Vandenhoek & Ruprecht.

Ach, N. (1935). *Analyse des Willens*. Berlin: Urban & Schwarzenberg (Handbuch der biologischen Arbeitsmethoden, Abt. 6, Teil E).

Al-Haytham, I. (1034/1989). *The optics.* Translated by A.I. Sabra, The Warburg Institute, University of London.

Allport, D.A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In H. Heuer & A.F. Sanders (Eds.), *Perspectives on perception and action*, (pp. 395–419), Hillsdale, NJ: Lawrence Erlbaum.

Aloimonos, Y. (1993). *Active perception.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Bennett, B.M., Hoffman, D.D., & Prakash, C. (1989). *Observer mechanics: a formal theory of perception*. San Diego: Academic Press.

Bingham, G.P., & Muchisky, M.M. (1995). "Center of Mass Perception": Affordances as dispositions determined by dynamics. In J.M. Flach, P.A. Hancock, et al. (Eds.), *Global perspectives on the ecology of human-machine systems*, *Vol. 1. Resources for ecological psychology*, (pp. 359–395). Hillsdale, NJ: Lawrence Erlbaum.

Bingham, J.P., & Pagano, C.C. (1998). The necessity of a perception-action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance*, **24**, 145–168.

Braunstein, M.L. (1972). Perception of rotation in depth. *Psychological Review*, **79**, 510–524.

Braunstein, M.L. (1994). Decoding principles, heuristics, and inference in visual perception. In G. Jansson, S.S. Bergström & W. Epstein (Eds.), *Perceiving events and objects*, (pp. 436–446). Hillsdale, NJ: Erlbaum.

Bruner, J.S., & Goodman, C.C. (1947). Value and need as organizing factors in perception. *Journal of Abnormal Social Psychology*, **42**, 33–44.

Brunswik, E. (1955). "Ratiomorphic" models of perception and thinking. *Acta Psychologica*, **11**, 108–109.

Campbell, D.T. (1959). Methodological suggestions from a comparative psychology of knowledge processes. *Inquiry*, **2**, 152–182.

Campbell, D.T. (1960). Blind variation and selective retention in creative thought as in other knowledge processes. *Psychological Review*, **67**(6), 380–400.

Campbell, D.T. (1974). Evolutionary epistemology. In P.A. Schilpp (Ed.), *The philosophy of Karl R. Popper*, (pp. 412–463). LaSalle, IL: Open Court.

DeLucia, P.R., Warren, R. (1994). Pictoral and motion-based depth information during active control of self motion: Size-arrival effects on collision avoidance. *Journal of Experimental Psychology: Human Perception and Performance*, **20**, 783–798.

Dreyfus, H.L. (1996). The current relevance of Merleau-Ponty's phenomenology of embodiment. *The Electronic Journal of Analytic Philosophy*, **4**, http://www.phil.indiana.edu/ejap/ (Spring 1996).

Eigen, M. (1998, September). *How to get from here to there in molecular evolution.* Paper presented at the Center for Interdisciplinary Research, Bielefeld, Germany.

Flach, J.M., Lintern, G., & Larish, J.F. (1990). Perceptual motor skill: A theoretical framework. In R. Warren & A. Wertheim (Eds.), *Perception and control of self-motion*, pp. 327–355. Lawrence Erlbaum Associates. Hillsdale, NJ.

Fodor, J.A., & Pylyshyn, Z.W. (1981). How direct is visual perception? Some reflections on Gibson's "Ecological approach". *Cognition*, **9**, 139–196.

Fowler, C.A., & Turvey, M.T. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables. In G.E. Stelmach (Ed.), *Information processing in motor control and learning*, pp. 1–40. New York: Academic Press.

Gibson, E.J. (1969). *Principles of perceptual learning and development.* Englewood Cliffs, NJ: Prentice Hall.

Gibson, J.J. (1966). *The senses considered as perceptual systems*. Boston: Houghton-Mifflin.

Gibson, J.J. (1979). *The ecological approach to visual perception.* Hillsdale, NJ: Lawrence Erlbaum.

Gigerenzer, G. (1997). Ecological intelligence: An adaptation for frequencies. *Psychologische Beiträge*, **39**, 107–125.

Gigerenzer, G., & Goldstein, D.G. (1996). Reasoning the fast and frugal way: Models of bounded rationality. *Psychological Review*, **103**, 650–669.

Gilchrist, J.C., & Nesberg, L.S. (1952). Need and perceptual change in need-related objects. *Journal of Experimental Psychology*, **44**, 369–376.

Gilden, D.L. (1991). On the origins of dynamical awareness. *Psychological Review*, **98**, 554–568.

Gilden, D.L., & Proffitt, D.R. (1989). Understanding collision dynamics. *Journal of Experimental Psychology: Human Perception and Performance*, **15**, 372–383.

Gilden, D.L., & Proffitt, D.R. (1994). Heuristic judgment of mass ratio in two-body collisions. *Perception & Psychophysics*, **56**, 708–720.

Ginsburg, G.P. (1990). The ecological perception debate: An affordance of the Journal for the Theory of Social Behaviour. *Journal for the Theory of Social Behaviour*, **20**, 347–364.

Grealy, M. (1997). *Tau-coupling in the control of gaze movements*. Paper presented at the 8th International Conference on Perception and Action, July Toronto.

Gruber, H., & Strube, G. (1989). Zweierlei Experten: Problemisten, Partiespieler und Novizen beim Lösen von Schachproblemen. *Sprache und Kognition*, **8**, 72–85.

Guay, M., Salmoni, A.W., & McIlwain, J. (1992). Summary knowledge of results for skill acquisition: Beyond Lavery and Schmidt. *Human Movement Science*, **11**, 653–673.

Hecht, H. (1996). Heuristics and invariants in dynamic event perception: Immunized concepts or non-statements? *Psychonomic Bulletin and Review*, **3**, 61–70.

Hecht, H. (1997). Subjective realism in a simulated squash game. In K.-P. Holzhausen (Ed.), *Advances in multimedia and simulation: Human-machine interface implications* (pp. 365–370). Proceedings of the Human Factors and Ergonomics Society Europe Chapter, Bochum.

Hecht, H. (in press). *Regularities of the physical world and the absence of their internalization*. Behavioral and Brain Sciences.

Hecht, H., & Bertamini, M. (in press). Understanding projectile acceleration. *Journal of Experimental Psychology: Human Perception and Performance*.

Hecht, H., Kaiser, M.K., & Banks, M.S. (1996). Gravitational acceleration as a cue for absolute size and distance? *Perception & Psychophysics*, **58**, 1066–1075.

Hecht, H., & Proffitt, D.R. (1991). Apparent extended body motions in depth. *Journal of Experimental Psychology: Human Perception and Performance*, **17**, 1090–1103.

Hecht, H., & Proffitt, D.R. (1995). The Price of expertise: Effects of experience on the water-level task. *Psychological Science*, **6**, 90–95.

Heft, H. (1989). Affordances and the body: An intentional analysis of Gibson's ecological approach to visual perception. *Journal for the Theory of Social Behaviour*, **19**, 1–30.

Heft, (1993). A methodological note on overestimates of reaching distance: Distinguishing between perceptual and analytical judgments. *Ecological Psychology*, **5**, 255–271.

Heider, F., & Simmel, M. (1944). An experimental study of apparent behavior. *American Journal of Psychology*, **57**, 243–259.

Helmholtz, H. von (1867). *Handbuch der physiologischen Optik. Bd. 3*. Leipzig: Voss. (3rd edition 1910).

HELMHOLTZ, H. VON (1894). Über den Ursprung der richtigen Deutung unserer Sinneseindrücke. *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, **7**, 81–91.

HEUER, H. (1993). Estimates of time to contact based on changing size and changing target vergence. *Perception*, **22**, 549–563.

HOCHBERG, J. (1981). On cognition in perception: Perceptual coupling and unconscious inference. *Cognition*, **10**, 127–134.

HOFFMAN, D.D. (1998). *Visual intelligence: How we create what we see*. New York: W.W. Norton.

HOMMEL, B. (1993). Inverting the Simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research* **55**, 270–279.

HOMMEL, B., MÜSSELER, J., ASCHERSLEBEN, G. & PRINZ, W. (1998). *The theory of event coding (TEC): A framework for perception and action.* Report # 3/1998, Max Planck Institute for Psychological Research.

HOWARD, I. (1978). Recognition and knowledge of the water-level principle. *Perception*, **7**, 151–160.

HOYLE, F. (1957). *The black cloud*. London: Heineman.

JOHANSSON, G. (1950). *Configuration in event perception.* Uppsala: Almqvist & Wiksell.

JOHANSSON, G. (1977). Spatial constancy and motion in visual perception. In W. Epstein (Ed.) *Stability and constancy in visual perception: Mechanisms and processes* (pp. 375–419). New York: Wiley.

KERZEL, D., & HECHT, H. (1997). Heading backward: Perceived direction of movement in contracting and expanding optical flow-fields. *Psychonomic Bulletin and Review*, **4**, 516–523.

KERZEL, D., HECHT, H., & KIM, N.G. (1999). Image velocity, not tau, explains arrival-time judgments from global optical Flow. *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 1540–1555.

KLIX, F. (1980). *Erwachendes Denken: Eine Entwicklungsgeschichte der menschlichen Intelligenz.* Berlin: VEB Deutscher Verlag der Wissenschaften.

KOFFKA, K. (1935). *Principles of Gestalt psychology*. London: Routledge and Kegan-Paul.

KRIST, H. (1992). Entwicklung naiver Bewegungskonzepte: Je flacher, desto weiter? *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, **24**, 171–183.

KÜLPE, O. (1893). *Grundriss der Psychologie.* Leipzig: Wilhelm Engelmann.

LEE, D.N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, **5**, 437–459.

LEEUWEN, C. VAN, & STINS, J. (1994). Perceivable information or: The happy marriage between ecological psychology and Gestalt. *Philosophical Psychology*, **7**, 267–285.

LIBEN, L.S. (1991). The Piagetian water-level task: Looking beneath the surface. In R. Vasta (Ed.), *Annals of Child Development*, **8**, London: Kingsleg.

LORENZ, K. (1935). Der Kumpan in der Umwelt des Vogels. *Journal für Ornithologie*, **83**, 137–213, 289–413.

LORENZ, K. (1973). *Die Rückseite des Spiegels: Versuch einer Naturgeschichte menschlichen Erkennens.* München: Piper.

MARR, D. (1982). *Vision.* New York: W.H. Freeman.

MAUSFELD, R. (1994). Hermann v. Helmholtz. Die Untersuchung der Funktionsweise des Geistes als Gegenstand einer wissenschaftlichen Psychologie. *Psychologische Rundschau*, **45**, 133–147.

MERLEAU-PONTY, M. (1945/1962). *Phenomenology of perception*, (translated by C. Smith), London: Routledge & Kegan Paul. Originally published as Phenomenologie de la perception, Paris, 1945.

MICHAELS, C.F., & CARELLO, C. (1981). *Direct perception*. Englewood Cliffs, NJ: Prentice Hall.

MICHOTTE, A. (1946/1963). *The perception of causality* (T.R., Miles & E. Miles, Trans.). London: Methuen. (Original work published 1946).

Müsseler, J., & Hommel, B. (1997). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception & Performance*, **23**, 861–872.
Neisser, U. (1976). *Cognition and Reality*. New York: Freeman.
Neisser, U. (1994). Multiple systems: A new approach to cognitive theory. *European Journal of Cognitive Psychology*, **6**, 225–241.
Neumann, O. (1990). Direct parameter specification and the concept of perception. *Psychological Research*, **52**, 207–215.
Neumann, O., & Prinz, W. (1987). Kognitive Antezedenzien von Willkürhandlungen. In H. Heckhausen, P.M. Gollwitzer & F.E. Weinert (Eds.), *Jenseits des Rubikon: Der Wille in den Humanwissenschaften*. Berlin: Springer.
Oudejans, R.R.D., Michaels, C.F., Bakker, F.C., & Dolne, M.A. (1996). The relevance of action in perceiving affordances: Perception of catchableness of fly balls. *Journal of Experimental Psychology: Human Perception and Performance*, **22**, 879–891.
Peper, L., Bootsma, R.J., Mestre, D.R., & Bakker, F.C. (1994). Catching balls: How to get the hand to the right place at the right time. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 591–612.
Poggio, T. (1990). Vision: The "other" face of AI. In K.A.M. Said, W.H. Newton-Smith, R. Viale & K.V. Wilkes (Eds.), *Modeling the mind* (pp. 139–154). Oxford: Clarendon.
Poggio, T., Torre, V., & Koch, C. (1985). Computational vision and regularization theory. *Nature*, **317**, 314–319.
Popper, K.R. (1972). *Objective knowledge: An evolutionary approach.* Oxford: Clarendon Press.
Prinz, W. (1987). Ideo-motor action. In H. Heuer & A.F. Sanders (Eds.) *Perspectives on perception and action*, (pp. 47–76). Hillsdale, NJ: Lawrence Erlbaum.
Prinz, W. (1998a). Die Reaktion als Willenshandlung. *Psychologische Rundschau, 49*, 10–20.
Proffitt, D.R. (1993). A hierarchical approach to perception. In S.C. Masin (Ed.), *Foundations of perceptual theory*, (pp. 75–111). Amsterdam: North-Holland/Elsevier.
Proffitt, D.R., Bhalla, M., Gossweiler, R., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic Bulletin & Review*, **2**, 409–428.
Proffitt, D.R., & Gilden, D.L. (1989). Understanding natural dynamics. *Journal of Experimental Psychology: Human Perception and Performance*. **15**(2), 384–393.
Proffitt, D.R., & Kaiser, M.K. (1995). Perceiving events. In W. Epstein & S.J. Rogers (Eds.), *Perception of space and motion, Handbook of perception and cognition (2nd ed.)* (pp. 227–261). New York: Academic Press.
Proffitt, D.R., & Kaiser, M.K. (1998). The internalization of perceptual processing constraints. In J. Hochberg, E.C. Caterette, & M.P. Friedman (Eds.), *Perception and cognition at century's end: Handbook of perception and cognition* (2nd ed.) (pp. 169–197). San Diego, CA: Academic Press.
Restle, F. (1979). Coding theory of the perception of motion configurations. *Psychological Review*, **86**(1), 1–24.
Riedl, R. (1975). *Die Ordnung des Lebendigen.* Berlin: Parey.
Riedl, R. (1980). *Biologie der Erkenntnis: Die stammesgeschichtlichen Grundlagen der Vernunft.* Berlin: Parey.
Riedl, R. (1992). *Wahrheit und Wahrscheinlichkeit: Biologische Grundlagen des Für-Wahr-Nehmens.* Berlin: Parey.
Riedl, R. (1996). Cognition of evolution: Can causal explanation overrule cognition? *Evolution & Cognition*, **2**, 88–107.
Rock, I. (1983). *The logic of perception.* Cambridge, MA: MIT Press.
Rock, I. (Ed.) (1997). *Indirect perception.* Cambridge, MA: MIT Press.
Roncato, S., & Rumiati, R. (1986). Naive statics: Current misconceptions on equilibrium. *Journal of Experimental Psychology: Learning Memory and Cognition*, **12**, 361–377.

Runeson, S. (1977). On the possibility of "smart" perceptual mechanisms. *Scandinavian Journal of Psychology*, **18**, 172–179.

Runeson, S. (1989, September). A note on the utility of ecologically incomplete invariants. *Newsletter of the International Society for Ecological Psychology*, **4**(1), 6–8.

Runeson, S. (1995). Heuristic judgment of mass ratio in two-body collisions. *Perception & Psychophysics*, **57**, 1262–1273.

Runeson, S., & Frykholm, G. (1983). Kinematic specification of dynamics as an informational basis for person-and-action perception: Expectation, gender recognition, and deceptive intention. *Journal of Experimental Psychology: General*, **112**, 585–615.

Salmoni, A.W., Schmidt, R.A., & Walter, C.B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin*, **95**, 355–386.

Savelsbergh, G.J.P., Whiting, H.T.A., & Bootsma, R.J. (1991). "Grasping" Tau. *Journal of Experimental Psychology: Human Perception and Performance*, **19**, 315–322.

Shapiro, L., & Epstein, W. (1998). Evolutionary theory meets cognitive psychology: A more selective perspective. *Mind & Language*, **13**, 171–194.

Shepard, R.N. (1984). Ecological constraints in internal representation. *Psychological Review*, **91**, 417–447.

Shepard, R.N. (1994). Perceptual-cognitive universals as reflections of the world. *Psychonomic Bulletin & Review*, **1**, 2–28.

Shimojo, S., Tanaka, Y., Hikosaka, O., & Miyauchi, S. (1996). Vision, attention, and action: Inhibition and facilitation in sensory-motor links revealed by the reaction time and the line motion. In T. Inui, J. McClelland & L. James, et al. (Eds.), *Attention and performance 16: Information integration in perception and communication*, (pp. 597–630). Cambridge, MA: MIT Press.

Simon, H.A. (1969). *The sciences of the artificial* (2nd edition 1981). Cambridge, MA: MIT Press.

Simon, H.A. (1982). *Models of bounded rationality*. Cambridge, MA: MIT Press.

Smeets, J.B.J., Brenner, E., Trébuchet, S., & Mestre, D.R. (1996). Is judging time-to-contact based on "tau"? *Perception*, **25**, 583–590.

Smith, B., & Casati, R. (1994). Naive physics. *Philosophical Psychology*, **7**, 227–247.

Smith, M.R.H., Flach, J.M., Stanard, T.W., Dittman, S.M. (1998). *An optical basis for controlling the timing of collisions: Beyond the tau hypothesis*. Manuscript submitted for publication.

Sternberg, S. (1969). The discovery of processing stages: Extension of Donder's method. *Acta Psychologica*, **30**, 376–315.

Stimpel, E. (1933). Der Wurf. *Neue Psychologische Studien*, **9**, 105–138.

Stumpf, P. (1911). Über die Abhängigkeit der visuellen Bewegungsempfindung und ihres negativen Nachbildes von den Reizvorgängen auf der Netzhaut. *Zeitschrift für Psychologie*, **59**, 321–330.

Thorndike, E.L. (1898). Animal intelligence: An experimental study of the associative process in animals. *Psychological Review Monographs*, *Supplement 8*, 109. Reprinted 1911, New York: Macmillan.

Todd, J.T., & Warren, W.H. (1982). Visual perception of relative mass in dynamic events. *Perception*, **11**, 325–335.

Todorović (1996). *Is kinematic geometry an internalized regularity*? Report No. 24/96, Zentrum für interdisziplinäre Forschung, Bielefeld, Germany.

Tolman, E.C., & Brunswik, E. (1935). The organism and the causal texture of the environment. *Psychological Review*, **42**, 43–77.

Tooby, J., Cosmides, L. (1989a). Adaptation versus phylogeny: The role of animal psychology in the study of human behavior. *International Journal of Comparative Psychology*, **2**, 175–188.

Tooby, J., & Cosmides, L. (1989b). Evolutionary psychology and the generation of culture: I. Theoretical considerations. *Ethology & Sociobiology*, **10**, 29–49.

Tooby, J., & Cosmides, L. (1992). The psychological foundations of culture. In J.H. Barkow, L. Cosmides & J. Tooby (Eds.), *The adapted mind: Evolutionary psychology and the generation of culture*. New York: Oxford University Press.

Tresilian, J.R. (1991). Empirical and theoretical issues in the perception of time to contact. *Journal of Experimental Psychology: Human Perception and Performance*, **17**, 865–876.

Tresilian, J.R. (1994). Approximate information sources and perceptual variables in interceptive timing. *Journal of Experimental Psychology: Human Perception and Performance*, **20**, 154–173.

Tresilian, J.R. (1995). Perceptual and cognitive processes in time-to-contact estimation: Analysis of prediction-motion and relative judgment tasks. *Perception & Psychophysics*, **57**, 231–245.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, **185**, 1124–1131.

Ullman, S. (1980). Against Direct Perception. *Behavioral and Brain Sciences*, **3**, 373–415.

Uttal, W.R. (1998). *Toward a new behaviorism: The case against perceptual reductionism*. Mahwah, NJ: Lawrence Erlbaum.

Vasta, R., Rosenberg, D., Knott, J.A., & Gaze, C.E. (1997). Experience and the water-level-task revisited: Does expertise exact a price? *Psychological Science*, **8**, 336–339.

Wang, Y., & Frost, B.J. (1992). Time to collision is signaled by neurons in the nucleus rotundus of pigeons. *Nature*, 356, 236–237.

Warren, W.H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance*, **10**, 683–703.

Watson, J.S., Banks, M.S., Von Hofsten, C., & Royden, C.S. (1992). Gravity as a monocular cue for perception of absolute distance and/or absolute size. *Perception*, **21**, 69–76.

Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt, II. *Psychologische Forschung*, **4**, 301–350.