INFORMATION, AFFORDANCES, AND THE CONTROL OF ACTION IN SPORT

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ABSTRACT

The theory of affordances, a conceptual pillar of the ecological approach to perception and action, has the potential to become a guiding principle for research on perception and action in sport. Affordances are opportunities for action. They describe the environment in terms of behaviors that are possible at a given moment under a given set of conditions. Affordances capture the tight coupling between perception and action, and allow for the prospective and moment-to-moment control of activity that is characteristic of fluent, fast-paced behavior on the playing field. We begin with an overview of the ecological approach and the principle of direct perception, using past research on interceptive action to illustrate how this principle has been put to work to capture information-movement relations in perceptual-motor skill. We then review theory and research on body-scaled, action-scaled, and social affordances, highlighting outstanding questions that provide opportunities for new research on affordances in the context of sport. We conclude with consideration of affordances as providing a functional semantics for sports.

INTRODUCTION

Throughout the course of any game or match, athletes encounter numerous opportunities for action on the playing field. There are opportunities to avoid obstacles, intercept moving targets, violently collide with players on the opposing team, pass through gaps, jump over barriers, throw and kick balls through openings and to targets, and so on. Because of the fast pace of many sporting activities, opportunities for action on the playing field often come and go in an instant. A gap between opposing players can open to afford passing through at one moment, and then collapse into an impenetrable barrier at the next moment. Opportunities for action can also materialize and dissolve in more subtle ways as a result of gradual changes in the player's action capabilities or changes in playing conditions. A ball that was catchable at the beginning of the game may be uncatchable at some later point due to fatigue. A sharp bend on a racetrack may be possible to take at maximum speed when traction is good, but not after traction is compromised by weather. To perform well on the playing field and to achieve victory, athletes must be acutely aware of the ever-changing opportunities for action afforded by the situation.

What sort of theory of perception and action is needed to do justice to the kinds of skills that athletes exhibit on the playing field? One might say that such a theory should have the following five ingredients. First, it should place primary importance on explaining the success and reliability of perception; less importance should be placed on misperceptions and illusions, which are far less frequent. Second, it should acknowledge that movement plays a critical role in perception, just as perception plays a critical role in movement. Third, it should place more importance on how we perceive those properties of the world that are most directly relevant to how we move to achieve goals. Fourth, it should account for the tight coupling between perception and action that is characteristic of perceptual-motor skill in sports. Finally, it should include an account of learning that captures changes accompanying practice.

We argue that the fundamental starting point for such a theory is a commitment to the idea that actors can achieve direct epistemic contact with their environments; that is, that they can know their environments in a way that is unmediated by internal representations. In short, we are looking for a theory of *direct perception* (Gibson, 1986; Michaels & Carello, 1981). One of the most fundamental conceptual barriers that stands in the way of developing a theory of direct perception is the deeply rooted assumption, dating back in the era of modern sensory physiology to at least Müller (1843), that the informational support for perception is inherently ambiguous. This assumption says that patterns in the distributions of energy (e.g., light, sound) cannot uniquely specify properties of the world, meaning that the mapping from patterned energy distributions to properties of the world is one-to-many rather than one-to-one (whereas a one-to-one mapping would constitute unique specification of properties of the world by patterns in the distribution of stimulus energy). Such patterns merely correlate with and provide cues or clues about the world. Together with prior knowledge and assumptions about the world, such cues can be used to infer properties of the world, much like a detective combines evidence with knowledge of the case to infer the events that led to a crime. Thus, what we perceive must be an interpretation of the world, not the world itself. Because according to this view perception of the world is mediated by an interpretation, the general term used to refer to such theories is *indirect perception*. Indirect perception theories maintain that perceivers are in contact with *representations* of the world, not with the world itself.

Theories of indirect perception are dominant, but they are more successful at explaining failures of perception than successes. Classic perceptual illusions such as the Ames Room[1] (Ames, 1952) are often used to make the case for indirect perception because they appear to lend themselves to explanations in terms of prior knowledge, assumptions, and inferences (but see Runeson, 1988). We remind the reader that we are looking for a theory of perception that does justice to feats of perception and action that athletes exhibit on the playing field. Any theory that takes illusions as its starting point is not likely to provide an adequate account of the success and reliability of perception in fast-moving, high-pressure environments like sport.

Committed to the idea that a theory of perception should do justice to its success, James J. Gibson (1986) sought to develop a theory of direct perception. Direct perception—perception that is not mediated by internal representations—can be possible if properties of the world are specified in patterns of stimulus energy. If properties of the world are unambiguously specified, perception does not have to involve processes of interpreting ambiguous cues about the properties of the world. Gibson's approach is an *ecological approach* because it stresses the reciprocity (Lombardo, 1987) or duality symmetry (Turvey & Shaw, 1999) of organisms and their environments. A first step toward meeting the challenge of a theory of direct perception is to reject the assumption that the input for perception is impoverished. In its place, Gibson and proponents of the ecological approach (Shaw, Turvey, & Mace, 1982) put forth the assumption that the distributions of energy surrounding an organism, when properly described, are rich with information that specifies action-relevant properties of the world. Justifying this assumption requires researchers to discover information in ambient energy arrays that specifies action-relevant properties and to show that movement is constrained by such information, which entails perhaps the even greater challenge of developing the conceptual and methodological tools for

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[1] The Ames Room is a distorted room that is specially configured to project a retinal image that is identical to that of a normal, rectangular room when viewed from a particular vantage point (i.e., through a peephole). The room is not actually rectangular—one corner opposite the vantage point is much farther away than the other, leading to the appearance that a person or object located in the more distal corner is smaller than a same-sized person or object in the more proximal corner.

discovering how properties of the world are specified in patterns of stimulus energy (Turvey & Shaw, 1995, 1999). In the next section, we briefly illustrate how Gibson's ideas have been put to work to understand a class of behaviors known as *interceptive actions*. This section is not intended to be a comprehensive review of research on interceptive actions. Rather, our goal is to give readers who are not already familiar with the ecological approach a sense of what it means to understand a perceptual-motor skill in terms of information-movement relations.

The main focus of this paper is on Gibson's theory of affordances, and its application to sport. We feel that the theory of affordances is ideally suited to capture the behavior of athletes on the playing field, and has great potential to become a guiding principle for research on perception and action in sport. In the second part of this paper, we will introduce the concept of affordances, review some of the empirical research on affordances, and point out potential applications to sport that provide opportunities for future research.

AN ECOLOGICAL APPROACH TO INTERCEPTIVE ACTION

Ecological psychologists wishing to meet the challenge of developing a theory of direct perception seek an understanding of the perceptual control of action in terms of information-movement relations. To illustrate this approach, we will focus on a class of behaviors, all of which require actors to intercept fast-moving targets. Such behaviors are referred to as interceptive actions, and are among the most impressive things that athletes routinely do on the playing field. In baseball, for example, fielders reach out with gloved hands to catch balls that approach speeds of 100 mph (~45 ms^{-1}). When catching a fly ball, outfielders guide the movement of their bodies and hands to the right place at the right time so that the ball is within reach before it hits the ground. Before the ball can be caught, the glove must be oriented more or less orthogonal to the direction of motion of the ball, the muscles of the arm must be readied for the ball's impact, and sometimes the entire body must be prepared so that the fielder can throw the ball in a particular direction as soon as possible after it is caught. Hitting a ball involves even more demanding spatiotemporal constraints because the batter should make contact when the bat is moving at its maximum speed while traveling in a particular direction.

A first step toward understanding interceptive actions is to identify and provide a formal description of the information that specifies action-relevant properties of the environment. In the 1970s, David Lee carried out extensive analyses of the changing optic array that revealed potentially important sources of information for a variety of activities, including catching and hitting (Lee, 1974, 1976; Lee & Lishman, 1977). It is difficult to overstate the lasting impact of Lee's discoveries. Although subsequent research raised questions about whether actors actually use some of the specific variables that Lee identified, his work inspired generations of researchers to look for information in changing patterns of optic and acoustic arrays (e.g., see Hecht & Savelsbergh, 2004).

Information about when

Because interceptive actions require actors to satisfy demanding temporal constraints, it is widely accepted that an approaching object's *time-to-contact* (TTC) must be accurately perceived in order to intercept the object. Lee (1976) demonstrated that TTC is optically specified by the ratio of an approaching object's size in the optic array to its rate of optical expansion, which he dubbed τ (tau). The appeal of τ is that it explains how actors directly perceive TTC, without first estimating the object's distance and approach speed. Furthermore, because τ is invariant over changes in the size of the approaching object, knowledge of the approaching object's size is not necessary. Thus, τ explains how time-to-contact, a potentially action-relevant property of the environment, can be directly perceived by detecting information in optic flow. Because τ is specific to time-to-contact (i.e., values of the optical variable τ are lawfully determined by the physics of object motion), detecting τ allows the animal to perceive time-to-contact without making any inferences or performing any mental calculations.

Numerous empirical studies designed to test the role of τ in the visual control of action followed Lee's early work. Most of the initial work was optimistic, claiming support for the use of τ by both humans (Lee, Young, Reddish, Lough, & Clayton, 1983; Savelsbergh, Whiting, & Bootsma, 1991) and non-human animals (Lee, Davies, Green, & van der Weel, 1993; Lee, Reddish, & Rand, 1991; Lee, Simmons, Saillant, & Bouffard, 1995; Wagner, 1982). Other studies provided support for the hypothesis that τ is used to time interactions with objects that are moving under the influence of gravity (e.g., a falling ball), even though TTC specified by τ is greater than actual TTC for accelerating objects[2] (Lee & Reddish, 1981; Lee et al., 1983). Humans' sensitivity to τ was documented in an extensive series of psychophysical studies by Regan and colleagues (see Regan & Gray, 2000 for a review).

Despite the initial enthusiasm for τ, recent research has been more critical (Hecht & Savelsbergh, 2004; Tresilian, 1999). Several researchers have reported that performance differs under binocular viewing conditions (Rushton & Wann, 1999; van der Kamp, Savelsbergh, & Smeets, 1997), suggesting that actors do not rely exclusively on τ (a monocular variable). Others have found effects of object size and approach speed that would not be expected if actors used τ (DeLucia, 1991; DeLucia & Warren, 1994; Fajen & Devaney, 2006; Michaels, Zeinstra, & Oudejans, 2001; Smith, Flach, Dittman, & Stanard, 2001). The claim that actors use τ to time interactions with accelerating objects has also been questioned

[2] τ specifies TTC assuming velocity is constant (i.e., first-order TTC). If velocity increases, as it does when objects fall under the influence of gravity, then actual TTC will be less than first-order TTC specified by τ.

(Michaels et al., 2001; Tresilian, 1997; Wann, 1996; Zago & Lacquaniti, 2005). Although this more recent work brings into question the role of τ in timing interactions with moving objects, it has also led to the discovery of other informational variables, thereby reinforcing the importance of detailed analyses of the optic array.

Information about where

Although a great deal of the research on interceptive actions has focused on information about TTC, catching and hitting also require actors to satisfy demanding spatial constraints. For instance, the passing distance—how closely an object will pass the actor—indicates how much (if at all) the actor needs to move to intercept a passing object. Both monocular and binocular information about passing distance has been identified (Bootsma, 1991; Regan & Kaushal, 1994) and tested (Bootsma & Peper, 1992; Gray & Sieffert, 2005; Jacobs & Michaels, 2006; Peper, Bootsma, Mestre, & Bakker, 1994). At least in principle, information about passing distance could be used together with information about TTC to move the hand into position at the right time to make a catch.

Catching also requires orienting the glove roughly orthogonal to the direction of motion of the ball, with little margin for error. If the catcher is using his or her hand rather than a glove, then the margin for error in hand orientation is even less. In certain sports, hitting also requires one to properly orient the bat, racket or paddle. For example, the ability of skilled tennis and table tennis players to hit balls to specific locations on the court or table would seem to depend on the pickup of information about the ball's direction of motion at the moment that it is struck. Regan and colleagues have shown that direction of motion in depth is specified by both monocular and binocular sources of information (see Regan, 1997 for a review). There is some evidence that observers overestimate the angle of approach of objects moving in depth (Harris & Dean, 2003; Harris & Drga, 2005), but the role of these variables in controlling hand orientation during actual catching and hitting has not yet been tested.

The role of perceptual attunement

Stepping back to look at the vast body of research on the informational basis for interceptive action, one might get the impression that the goal is to identify *the* optical variable that is used by all actors all of the time. It is important to acknowledge that people are remarkably flexible in their ability to adapt to changes in task constraints, criteria for success, and the availability of information. Some degree of flexibility can be achieved by *perceptual attunement* to different informational variables as conditions change.

Perceptual attunement is particularly relevant to the study of perception and action in sport because most sports-related activities are skills that require extensive practice to master. The notion of perceptual attunement implies that differences between experts and novices reflect, in part, differences in the informational variables upon which experts and novices rely. Indeed, recent evidence from a range of perceptual (Jacobs, Runeson, & Michaels, 2001; Michaels & de Vries, 1998) and perceptual-motor (Jacobs & Michaels, 2006; Smith et al., 2001; van der Kamp et al., 1997) tasks suggests that novices rely on variables that do not specify the relevant property, but with practice converge toward specifying variables. For example, subjects in Smith et al. completed several sessions of practice on a ball hitting task with precise temporal demands. Because movement time was fixed, the task required subjects to learn the precise moment at which to initiate movement to hit the approaching ball. They found that novices relied on optical variables that were not invariant over changes in the size and speed of the approaching ball, leading to biases in performance when those factors were manipulated. With practice, however, subjects learned to rely on optical variables that allowed them to perform the task more successfully across variations in size and speed. Similar findings have been reported in studies of catching (Jacobs & Michaels, 2006; van der Kamp et al., 1997), helping to establish perceptual attunement as a general principle that underlies learning and flexibility. This is important because it shifts the focus of research from finding *the* informational variable for a given task to understanding the factors that influence changes in the informational variables upon which actors rely. Knowledge of those factors could have important practical implications for sports, as training could focus on developing proper perceptual attunement to relevant variables under different performance conditions.

The information-based approach: Summary

To summarize, the ecological approach challenged researchers to identify information in changing patterns of optic flow that specifies action-relevant properties of the environment, and to show how this information is used in the control of action. Studies of the informational basis for interceptive actions such as catching and hitting have proven to be particularly fruitful in efforts to identify informational variables that support the control of action. Information about when the ball will pass within range, where it will be at that point in time, and its direction of motion has been identified and empirically tested. Although questions remain about which particular optical variables are used and how they are used, the ecological approach has led to a deeper understanding of how athletes satisfy demanding spatial and temporal constraints on the playing field. Further, the more fundamental claim that movements are guided by information in the changing optic array is now well established.

The information-based approach, more so than any other aspect of ecological psychology, has made its mark on the study of perception and action in sport. By comparison, other aspects of the ecological approach are perhaps underappreciated. In particular, we feel that the *theory of affordances*, which lies at the heart of the ecological approach, ought to be more seriously considered as a guiding principle for research in the sport sciences. In the next section, we explain the theory of affordances, review some of the empirical research on affordance perception, and point out its application to sport.

AFFORDANCES

The concept of affordances

The concept of affordances was introduced by Gibson (1966, 1977, 1986) to describe the opportunities for action provided by the environment for an animal. A given environment may afford a multitude of behaviors for an animal. Consider a soccer pitch (field) as an example environment. The pitch itself affords upright standing and locomotion, the ball affords kicking, and opposing players afford avoiding, to name a few of the many affordances of this environment. To perceive an affordance, in Gibson's view, is to perceive how one can act when confronted with a particular set of environmental conditions. Gibson's rather simple and modest claim, in the context of the soccer pitch example, is that a soccer pitch looks walk-on-able and a ball looks kick-able to a person who possesses the action capabilities necessary for walking and for kicking.

We believe the affordance concept is ripe for application in sport. In sport the outcome of a match can often hinge on an athlete's ability to determine when a behavior is possible, and when it is not. For example, a basketball player must be able to determine whether it is possible to pass the ball around a defender to reach an open teammate, or whether the defender will be able to intercept the pass and deny an attempt at a game-winning basket. Compared to other developments in the ecological approach, such as the notion of continuous, information-based control (reviewed in the previous section), affordances have received less attention from the sport science community (see Williams, Davids, & Williams, 1999, for instance). In this section we highlight some key features of Gibson's (1986) theory of affordances, and discuss some varied takes on the affordance concept in the perception-action literature. We then review a sample of the vast amount of empirical research on affordance perception as well as some more recent empirical and theoretical efforts to extend the theory of affordances to social contexts involving more than one actor. Along the way we highlight some of the many implications of affordances for sport.

Key features of affordances

Affordances are Real. In Gibson's (1986) formulation affordances have a real existence—they are part of the ontology (Turvey, 1992). The real existence of affordances as ontological entities means that, in principle, affordances can be specified in patterns of stimulus energy (i.e., there is information about affordances available to the actor). If this is the case, affordances need not be conceived by the actor via some sort of constructive, cognitive processing, but rather they can be directly perceived.

Affordances are Animal-Specific. Affordances are not inherent in objects or environments themselves. However, they are animal-specific, meaning that they are defined relative to the action capabilities of a given animal. A regulation-size soccer ball may afford kicking and dribbling for an adult, but may not afford kicking and dribbling for a toddler, for instance (cf. Araújo, Davids, Bennett, Button, & Chapman, 2004). Affordances thus refer to the relation between an animal and its environment. This feature of affordances is not incompatible with the claim that affordances are ontologically real. The fact that affordances are *relational properties*, and that the relation in question refers to a specific animal, does not make them unreal. A relation really does exist between the size and mass of a soccer ball and the size and mass of an infant's body (see Huettel, Polger, & Riley, 2003, for a similar argument).

Affordances Capture the Reciprocity of Perception and Action. Affordances describe the environment in terms of how animals can act. By couching perception in the language of action, affordances capture the reciprocity of perception and action. Perception and action perpetually feed one another. Gibson (1966, 1986) recognized that any complete theory of perception must account for that fundamental fact and consider perception and action jointly rather than (as is the tendency in cognitively oriented approaches) treating them as separate problems that can be solved independently and afterwards connected. This is one of the reasons why we think the concept of affordances is so ideally suited for investigating perceptual-motor skill in sports.

Affordances Allow for Prospective Control. Perceiving affordances allows actors to prospectively control their behavior (Turvey, 1992; Turvey & Shaw, 1995). Recall from the previous section that the prospective control of catching implies that movements are guided on the basis of information about future states of affairs; e.g., information about whether or not the ball will be caught if current conditions (hand and ball velocity) persist. More generally, prospective control refers to the means by which actors adapt behavior in advance to the constraints and behavioral opportunities in the environment. Perception thus plays a preparatory role in action as well as an on-line role in tuning action as it unfolds. Prospective control is crucial for skilled behavior in everyday situations as well as in athletic performance (Kim & Turvey, 1998; Lee, 1980). In the absence of prospective control, action would be reduced to mere reaction, which would not suffice in many fast-paced sport environments.

Affordances are Meaningful. Gibson (1986) proposed that the environment is perceived fundamentally in terms of what it affords the perceiver, rather than in terms of animal- (and action-) neutral properties such as extent, shape, or color, per se. Such properties, Gibson noted, are devoid of any meaning in and of themselves. If animals are perceptually sensitive only to those kinds of properties of the environment, as most other modern theories of perception have claimed since the work of Helmholtz (1867/1925), then the meaning of perception would have to be supplied by the perceiver through some sort of higher-order cognitive processing. In contrast, affordances are inherently meaningful in that they describe what an animal can or cannot do in a given environment. If affordances can be perceived directly—rather than perceived indirectly by first perceiving lower-order, animal-neutral, physical properties of the environment and then elaborating those sensory experiences by cognitive processing of some sort—then perception can be meaningful without the meaning being provided by constructive cognitive processes that mediate between sensation and perception. Gibson proposed that direct perception of affordances is possible because lawful processes dictate the relation between patterns of stimulus energy (i.e., the optic array) and the environmental properties that give rise to those patterns. If patterns of stimulus energy are specific (i.e., lawfully relate) to the environment, the environment can be perceived without the process requiring cognitive mediation.

Affordances are Dynamic. Opportunities for action come and go on a moment-to-moment basis. Affordances may arise and dissolve with movements of the actor even though the surfaces and substances in the actor's environment remain static, or as changes occur in the actor's environment while the actor remains static. The world of behavioral opportunities is dynamic (Kirsh, 1991; Turvey, 2004; Turvey & Shaw, 1995, 1999). This key feature of affordances is easily appreciated in the fluid sport environment. A fly ball in baseball may be catchable for a brief period after the ball is hit by the batter. But if the fielder gets off to a slow start, then at some point before it lands, the ball will become uncatchable. Thus, the situation can change from one that affords catching to one that does not afford catching in an instant. Similarly, changes in the actor's environment can give rise to changes in what behaviors are possible. At one moment in a match, a teammate may be open, and a pass to that teammate afforded. Milliseconds later a defender may slip into the passing lane, and the pass is no longer possible. Action possibilities can evolve and devolve rapidly as in these examples, and also over longer time scales, as when a fatigued player late in a match cannot accelerate quickly enough to catch a pass would have been possible to catch earlier in the match, before the onset of fatigue. Although the "quicksilvery" nature of affordances has perhaps been less well appreciated than the preceding features, it cannot be ignored if the affordance concept is to have utility for understanding perception-action in the dynamic context of sports.

Varied takes on the affordance concept

Since Gibson's original writings on affordances there have been efforts to refine the affordance concept (see, e.g., Jones, 2003). One such effort led Turvey (1992) to define affordances as dispositional properties of the environment that are complemented by dispositional properties of animals termed effectivities. Alternatively, Stoffregen (2003) defined affordances as emergent properties of animal-environment systems, and claimed that affordances are not properties of the environment alone. Instead, according to Stoffregen's perspective, affordances are undefined without jointly considering properties of both the animal and environment. Michaels (2003) defined affordances not as properties of the environment or of the animal-environment system, but instead as the possible actions themselves (e.g., *walking* is an affordance of a roughly horizontal, extended surface that is sufficiently dense relative to an animal's mass; in contrast, defined in terms of the environment or the animal-environment system, the affordance would not be identified as *walking*, per se, but as *walk-on-able*). Other theorists have sought to situate affordances within more traditional cognitive and information-processing frameworks (e.g., Vera & Simon, 1993), treating affordances as if they are conceived rather than perceived (see Turvey, 1975; Turvey & Shaw, 1995, 1999). More recently, advocates of embodied cognition perspectives have invoked the affordance concept in efforts to understand how putatively "higher-order" forms of cognitive activity might be rooted in putatively more fundamental perceptual-motor exchanges between animals and their environments (e.g., Barsalou, 1999; Glenberg, 1997). It is not our goal in the present work to argue for one of those specific takes on the affordance concept to the exclusion of others, with the exception that (as can be intimated from the previous section) we do not endorse information-processing or representational accounts of affordance perception (see, e.g., Turvey, Shaw, Reed, & Mace, 1981). For our discussion of the importance of affordances for sport, it is sufficient to think of affordances as properties of animal-environment systems that can be specified in patterns of stimulus energy and that can therefore be directly perceived.

Research on affordances

Empirical research has demonstrated that people can perceive (by means of vision, hearing, touch, etc.) a variety of affordances with impressive accuracy, including affordances of step-on-ability (Warren, 1984; Wraga, 1999), step-across-ability (Cornus, Montagne, & Laurent, 1999), sit-on-ability (Mark, 1987; Mark, Balliet, Craver, Douglas, & Fox, 1990), reachability in the horizontal (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Mark, Nemeth, Gardner, Dainoff, Paasche, Duffy, & Grandt, 1997; Rochat & Wraga, 1997) and vertical planes (Pepping & Li, 1997, 2000), pass-through-ability (Warren & Whang, 1987; Wraga, 1999), pass-under-ability (van der Meer, 1997; White & Shockley, 2005), and stand-on-ability of a slope (Fitzpatrick, Carello, Schmidt, & Corey, 1994). Many of these scenarios that have been investigated in the laboratory have analogues in sport. As an example of such an analogue, the situation that subjects encounter in studies of pass-ability is similar to that encountered in American football, where running backs must be able to perceive whether holes in the line of defenders afford passage. In the case of football, however, the gaps in the line are dynamic rather than static—the gaps' locations and widths are constantly changing. No research has investigated the perception of affordances in such a scenario, although Gibson and Crooks' (1938) work on fields of safe passage in driving (research that preceded Gibson's development of the theory of affordances) anticipated such problems. The affordance of reach-ability is important in a number of sports, particularly in ball sports where an athlete must determine if a passing ball is reachable, such as a goalie in soccer. In softball, a fielder needs to be able to determine if a ball is reachable from her current location, or whether she will need to move to reach the ball, and the first baseman must determine whether the fielder's throw is catchable without removing her foot from the base. Although more work on this topic is necessary, one study by Peper et al. (1994) found that seated subjects could accurately judge the catchability of balls that passed within or just outside of reach.

Two categories of affordances have been investigated extensively: *Body-scaled* affordances, in which the relation between some measurable dimension of the animal's body in relation to a reciprocal property of the environment determines whether an action is possible (e.g., a person's leg length relative to the height of a step), and *action-scaled affordances*, in which how the animal can behave relative to the environment (e.g., how fast the person can arrive at some location, or how much force they can produce with their muscles) determines whether an action is possible. Before reviewing the literature on body-scaled and action-scaled affordances, it is worth pointing out that not all affordances fit neatly in one of these two categories. For example, whether an object affords reaching by jumping is determined partly by body scale (i.e., the person's height and arm length) but also by the actor's force-generating capabilities (i.e., the amount of vertical force the person can produce). Affordances that are both body- and action-scaled may be prevalent in sports. Pepping and Li (1997), for instance, investigated perception of the maximum height to which volleyball players could jump in order to block an opponent's shot. They found that even novice volleyball players could accurately perceive maximum block-able height. More research on these kinds of affordances is needed and may be highly relevant for analyses of sport. Since most research has focused on either body-scaled or action-scaled affordances, we will focus on research on each of those types of affordances in the next sections.

Body-scaled affordances

A number of affordances can be described primarily in terms of the relation between some dimension of an animal's body, such as leg length, and a complementary property of the environment, such as the height of a step. For instance, if the height of a step is less than or equal to 0.88 times a person's leg length (Warren, 1984), then the step is *climbable* for that person. Affordances of this kind can be termed *body-scaled affordances* (though see Konczak, Meeuwsen, & Cress, 1992, for a discussion of factors other than body size that determine whether a step is climbable). Body-scaled affordances can be measured on a scale that is intrinsic to the perceiver (e.g., in units of leg length) rather than according to an extrinsic measurement system such as inches or centimeters. Perceiving the environment in body-scaled units thus relates the environment directly to the perceiver's action capabilities. Warren (1984) found that perceivers were extremely accurate at perceiving the maximum climbable step height, as well as at perceiving the energetically optimum stair height, which corresponds to 0.26 times a person's leg length.

Warren's (1984) groundbreaking research demonstrated that people can perceive body-scaled affordances very accurately, but his study left open how exactly they went about doing so. In principle, Warren's participants could have perceived step height in an extrinsic measurement frame and then used a cognitive strategy of dividing the extrinsically scaled step height by a stored representation of leg length, measured in the same extrinsic units. Affordance perception could thus be conceived as an indirect process, in line with more traditional theories of perception. Thinking of affordances in this way would fail to capture the richness of Gibson's (1986) broader theoretical approach, however, and would amount to little more than an ad-hoc effort to revise traditional, constructivist theories in order to tie perception and action together. Theoretical arguments aside, the indirect, cognitive strategy seems unlikely on the basis of empirical evidence. Mark (1987) found that after small amounts of practice participants could accurately judge their new maximum sitting height when wearing blocks attached to the feet (the blocks raised the maximum sitting height by making participants 10 cm taller), but the participants inaccurately estimated the height of the blocks. Accurate estimation of block size would be requisite for the sort of cognitive strategy just described.

Body-scaled affordances could be perceived directly by detecting optical information that delivers the environment in body-scaled terms to the perceiver's perceptual systems. In that case, the perceiver does not have to perform a cognitive operation to relate the environment to his or her own body scale. One such source of information is eyeheight-scaled optical information (Lee, 1974, 1980; Sedgwick, 1973, 1980). A perceiver's eyeheight can be optically specified, which in turn yields the dimensions of other objects in the optic array specified as ratios of object dimensions to eyeheight (see Warren & Whang, 1987). Because a perceiver's eyeheight is related to other body dimensions, such as leg length, eyeheight-scaled information about surfaces and objects in the environment relates the environment to the perceiver's body and thus provides a natural basis for perceiving body-scaled affordances. The results of several studies are consistent with the use of eyeheight-scaled optical information for perceiving a number of affordances (Carello et al., 1989; Mark, 1987; Warren & Whang, 1987; White & Shockley, 2005; Wraga, 1999). Warren and Whang had perceivers make judgments of pass-through-ability of an aperture. The aperture rested on a false floor that could be raised, thereby reducing specified eyeheight. Participants identified narrower apertures as pass-through-able when the false floor was raised (i.e., when specified eyeheight was reduced), but when aperture widths were scaled by effective eye height there was no difference in aperture width between the raised and normal floor conditions. Those results provide strong, direct evidence for the use of eyeheight-scaled information in affordance perception.

An avenue for future research concerns the use of implements that modify an athlete's capabilities, such as by extending the athlete's effective body dimensions (e.g., by extending reach). A number of such implements are used in different sports, such as gloves in baseball and softball or lacrosse sticks. Research on the haptic perceptual subsystem of dynamic touch (see review by Carello & Turvey, 2000) has shown that people can perceive distances reachable by means of a hand-held object (Solomon & Turvey, 1988). Physical properties of the object—namely the object's spatial distribution of mass—play a determining role in perceiving what is reachable using the object. In some cases, depending on an implement's spatial distribution of mass, actual reachability using the implement and haptically specified reachability may be discrepant, requiring the user to adapt or calibrate to the implement in order to accurately perceive actions that are possible using the implement (we will discuss the issues of learning, adaptation, and calibration in a later section). The affordance concept has drawn considerable interest in the fields of human factors, ergonomics, and design (e.g., Norman, 1988; Warren, 1995; Zaff, 1995), and recent research suggests a role for considering affordances in the design of sporting equipment (Araújo et al., 2004; Hove, Riley, & Shockley, 2006).

Action-scaled affordances

Whereas some affordances are clearly constrained by actors' body dimensions, others are constrained by their action capabilities. In baseball, for example, the catchableness of a fly ball depends less on fielders' body dimensions, and more on their running (and perhaps even jumping) capabilities. Accordingly, such affordances are characterized as action-scaled rather than body-scaled.

The perception of action-scaled affordances is critical to successful performance on the playing field. Consider, for example, a weak fly ball hit in front of an outfielder, and suppose that the outfielder is too slow to reach the landing location on time. If the fielder runs as quickly as possible toward the landing location, and arrives a moment too late, then he may need to make a difficult play to keep the ball from skipping by. If the ball is uncatchable, the smarter play is to slow down and let the ball bounce far enough away that it can be easily caught after it hits the ground. In short, good outfielders reliably distinguish between two categories of action: catchable and uncatchable balls. Speaking in more general terms, good athletes know what they can and cannot do, and rarely attempt to do things that are beyond their limits.

The ability to perceive the catchableness of fly balls was demonstrated by Oudejans, Michaels, Bakker, and Dolné (1996) in one of the few studies of action-scaled affordances. They projected tennis balls into the air in front of and behind the subject, varying flight duration and landing location. Subjects were instructed to either judge whether or not the ball was catchable, or actually attempt to catch the ball. They found that judgments of catchableness closely corresponded to actual catchableness, provided that the fielders were allowed to move for a brief (1 s) period before making the judgment. These results demonstrate that actors can indeed perceive affordances that are constrained by their action capabilities, just as they can perceive affordances that are constrained by their body dimensions.

The perception of action-scaled affordances is important, not only in making decisions about different categories of action (i.e., to try to catch the ball on a fly or let it bounce), but also in the ongoing guidance of action. This is because the limits on actors' capabilities to run, turn, jump, stop, etc., place critical constraints on successful performance. Actors must be sensitive to those constraints. When outfielders pursue fly balls, they have some degree of flexibility in the trajectory that they can follow to the landing location. They can get off to a slow start, gradually speed up, and catch the ball while running, or they can run quickly to the landing location and wait for the ball. They can follow a straight path, or they can follow a curving path. Although some flexibility can be tolerated, fielders must move in such a way that the speed required to catch the ball never exceeds their maximum running speed. That is, they must move in such a way that catching is always afforded. Fajen (under review-a) referred to this as *affordance-based control*.

Recent experiments on braking provide evidence that actors take the limits of their capabilities into account when guiding their movements on the basis of visual information (Fajen, 2005a, 2005c). In these experiments, subjects used a joystick as a hand brake to decelerate to a stop as close as possible to a row of stop signs. Fajen (2005a) found that when the deceleration required to stop was well below the maximum deceleration of the brake, then braking behavior was quite variable. However, when required deceleration approached maximum deceleration, subjects almost always increased brake pressure. Thus, deceleration is continuously adjusted in a way that takes into account the limits of one's braking capabilities; that is, braking is controlled in such a way that safe stopping is always afforded. When three levels of brake strength (weak, medium, and strong) were used in another study (Fajen, 2005c), subjects in the weak and strong brake conditions initiated deceleration earlier and later, respectively, than subjects in the medium brake condition. However, when measures of braking behavior were scaled against maximum braking capabilities for each group, behavior was invariant across groups. Just as subjects in Warren's (1984) study perceived riser height in intrinsic units related to the dimensions of the body, subjects in Fajen (2005c) perceive needed deceleration in intrinsic units related to their braking capabilities.

One issue concerning action-scaled affordances that warrants future research is the accuracy and precision with which action-scaled affordances can be perceived. This is an important issue because athletes often try to gain an advantage by pushing the limits of their capabilities. Not only are good athletes stronger, faster, and quicker, but they also better perceive what they can and cannot do. Differences between athletes at different skill levels may reflect (at least, in part) differences in perceptual attunement. Recall from the first section of this paper that perceptual attunement refers to changes over a period of practice in the informational variables upon which actors rely. To the extent that novices rely on non-specifying variables or cues to perceive action-scaled affordances, their ability to reliably distinguish between possible and impossible actions across a range of conditions will be degraded (Fajen & Devaney, 2006). This issue could be investigated by studying highly skilled athletes when they are performing near the limits of their action capabilities.

Another outstanding question is how actors perceive affordances that are both body-scaled and action-scaled. One of the few studies to investigate the perception of such affordances is Cesari, Formenti, and Olivato (2003). They pointed out that the climbability of stairs depends not only on body dimensions (e.g., leg length) but also on action capabilities (e.g., strength and flexibility). They identified a new variable – the ratio of the height of the step to the distance (before movement was initiated) from the feet to the top of the step – that was invariant across participants with different body dimension and stair climbing abilities. This is remarkable because it provides a possible informational variable that could be used to guide action when climbing stairs in a way that takes into account differences in body dimensions and action capabilities.

The necessity of calibration

Body dimensions and action capabilities are not fixed, but often change across both short and long time scales. The length of limbs increases during the normal growth period. In sport, players' effective body dimensions are altered by implements such as gloves, bats, and sticks. Action capabilities change across short time scales as a result of factors such as fatigue, injury, and changes in load, and across longer time scales as a result of development and training. When body dimensions and action capabilities change, actions that were once possible may become impossible (or vice-versa). Some form of learning must be involved in the perception of affordances to allow actors to adapt to such changes. Such learning can be thought of in terms of perceptual-motor *(re-)calibration*. In measurement devices, calibration establishes a mapping between the units in which the measurement is taken and some known units, and recalibration updates the mapping if the characteristics of the device change. In perception and action, calibration and recalibration are necessary to establish and update the mapping between the units in which the relevant properties of the world are perceived, and the units in which the action is executed.

To illustrate the role of (re-)calibration in the perception of body-scaled affordances, suppose that the ratio of maximum seat height to eyeheight for a particular actor is 0.40 (Mark, 1987). If the actor is calibrated, then she can use eyeheight scaled information about surface height to directly perceive the sit-on-ability of a surface. Now suppose that the actor's leg length is suddenly increased by strapping 10 cm blocks to her feet, as in Mark's study. Because both maximum seat height and eyeheight increase by the same amount (10 cm), the ratio also increases. Some surfaces that previously did not afford sitting (e.g., those that are slightly above 0.40) now do afford sitting. However, without the ability to recalibrate, the actor would incorrectly perceive that such surfaces are not sit-on-able. Thus, recalibration is necessary to learn a new mapping between eyeheight-scaled information about seat height and the affordance of sitting. Mark found that subjects were able to relearn the maximum seat height that afforded sitting, confirming that such recalibration is possible. Further, he showed that recalibration does not require actual practice with the task of sitting. Even minimal activity (e.g., leaning) with 10 cm blocks on one's feet leads to recalibration, although subjects who were completely restricted from moving did not recalibrate (Mark, Balliett, Craver, Douglas, & Fox, 1990).

Fajen (2005c; under review-b) investigated recalibration in the context of action-scaled affordances by modifying subjects' braking capabilities in a simulated braking task. Subjects rapidly recalibrated, even when they were unaware that their braking capabilities suddenly changed, and even when the screen turned black one second after braking was initiated (well before reaching the intended stopping point). The latter result suggests that recalibration to changes in action capabilities does not require feedback about the outcome of the action, just as Mark (1987) showed that recalibration to changes in leg length (brought about by wearing blocks) does not require practice sitting.

Calibration makes it possible for actors to perceive the world in intrinsic units even after changes in body dimensions and action capabilities. For a properly calibrated actor, body-scaled and action-scaled affordances can be directly and reliably perceived by simply picking up the relevant information. Although recalibration occurs quite rapidly, it is likely that further experience leads to further improvements in calibration. One might say that top athletes are able to perform near the limits of the action capabilities because years of practice have left them so precisely calibrated. If so, then more research on calibration in the context of sport should be conducted, with the goal of designing training sessions that facilitate proper calibration.

Research on learning to perceive affordances during perceptual-motor development (see review by Adolph & Berger, 2006) may have important additional implications for athletes and trainers. This body of research has revealed that learning and calibration to changing action capabilities may not transfer to nearly identical environmental conditions. An infant that has just learned to walk may, for example, try to traverse downhill slopes that were discovered to be safely traversable when crawling, but that are not safely traversable when walking (Adolph, 1997). After some amount of experience walking the infant comes to learn which layouts of surfaces afford locomotion by walking. The potential lesson for sports is that affordance learning may be quite specific to (i.e., may not transfer across) modes of action. As an athlete's action capabilities change with training and experience, there may be a need to continually retune and re-calibrate in order to ensure successful control of action (cf. Campos, Anderson, Barbu-Roth, Hubbard, Hertenstein, & Witherington, 2000).

Finally, it is important to point out that calibration and attunement are not synonymous, although both play important roles in learning to perceive affordances. Recall that (re-)attunement refers to changes in the informational variables upon which one relies. An actor can be properly attuned, in the sense that she is relying on an informational variable that invariantly specifies the relevant property, but not properly calibrated. Thus, to reliably perceive affordances, both attunement and calibration are necessary.

Affordances in a social context

Social interactions are among the most fundamental of human behaviors, and other people are fundamental components of an individual's environment. No account of perception-action is thus complete without consideration of the social aspects of perception-action (Marsh, Richardson, Baron, & Schmidt, 2006). This is especially true when considering perception-action in team sports, and possibly even in some "individual" sports, since individuals are usually competing against others who may afford certain behaviors. Early theoretical treatments of ecological social psychology and social affordances were offered by Baron and Boudreau (1987), Baron and Misovich (1993), and McArthur and Baron (1983). Three categories of social affordances can be described: Affordances *for* another person (i.e., what actions another person can perform under a given set of environmental conditions), affordances for *joint action* (i.e., what actions can the perceiver and another agent or agents perform cooperatively), and affordances *of* another person (i.e., what actions another person afford the perceiver).

Perceiving Affordances for Other People. Although there is some debate regarding whether perceiving the actions possible for another person constitute cases of affordance perception or rather merely perception of relations (Michaels, 2003), evidence indicates that people can accurately perceive what actions are possible for another person (Ramenzoni, Riley, Davis, & Snyder, 2005; Rochat, 1995; Stoffregen, Gorday, Sheng, & Flynn, 1999; Zaff, 1995). The reported accuracy of perceptual reports of affordances for another actor has varied from ball-park accuracy (≤ 10% error or less; Stoffregen et al., 1999) to very high levels of accuracy (< 1% error; Ramenzoni et al., 2005). In some cases, however, affordance judgments for another actor have been less accurate than judgments for oneself. For instance, Zaff (1989; see also Zaff, 1995) reported that while people could perceive the affordance of overhead reachability for another actor, judgment errors increased as differences between the perceivers' and the actors' reaching heights increased (that error decreased with practice, however). Rochat (1995) found that children made errors in perceiving what is reachable for an adult, although children nevertheless clearly differentiated responses for adults and for themselves. In addition, adults in Rochat's study were not prone to such errors when making judgments for children, suggesting a developmental basis for the children's errors.

In all, evidence favors the idea that people can perceive affordances for another actor. What remains less thoroughly documented is the informational basis of this perceptual ability. Stoffregen et al. (1999) found using point-light displays of a walking actor that information contained in movement kinematics was sufficient to support the visual perception of affordances of maximum and preferred sitting heights for the actor, provided that the kinematic displays preserved information about the relation between the actor and the chair. Ramenzoni, Riley, Shockley, and Davis (2006) have shown that perception of affordances for overhead reaching is influenced by manipulating the perceiver's eyeheight, suggesting that eyeheight-scaled optical information is used when perceiving at least one example of body-scaled affordances for another person.

Perceiving affordances for another person has significance for sport on a number of levels. Athletes need to be able to perceive affordances for their opponents, and tailor their actions to result in situations where certain actions are not possible for the opponent. For example, in tennis a player may need to know what shots afford returning by the opponent, and attempt to deliver a shot that is not returnable. In basketball, a shooter must avoid attempting a shot when blocking the shot is afforded a defender. In other cases, an athlete needs to know what actions are afforded a teammate. In American football, a quarterback must know how high a receiver can jump to reach a pass that at the same time would not be reachable by a defender. Affordance analyses of these kinds of situations that occur in various sports may provide a useful theoretical framework for sport science research.

Perceiving Affordances for Joint Action. When two people come together with a common goal the action capabilities of the dyad in many cases will exceed (or at least differ from) the action capabilities of either individual (Marsh et al., 2006). There will thus be affordances of the dyad-environment system—affordances for joint action—that do not exist for either actor alone under the same environmental circumstances. Very little research has been conducted on perceiving affordances for joint action. In experiments by Isenhower, Marsh, Carello, Baron, and Richardson (2005) and Richardson, Marsh, and Baron (in press), pairs of participants were faced with the task of transferring planks of varying lengths from one table to another. Very short planks were grasped by one participant using one hand. At a critical ratio of plank length to hand size, participants spontaneously adopted a two-handed grasp of the planks. At another critical ratio of plank length to an actor dimension (in this case, arm span), participants exhibited a transition from one-person to two-person lifting. In experiments that only required perceptual judgments of intra- and inter-personal graspability perceivers exhibited prospective perceptual sensitivity to those action boundaries even though they did not have the opportunity to perform the actions in question. These results indicate that people are sensitive to affordance boundaries that span more than one actor, which may be critical for the prospective control of joint action (Sebanz, Bekkering, & Knoblich, 2006).

In sport, joint action may be an important factor related to teamwork. Affordances for joint action indicate what a group or team of athletes is capable of doing when coordinating their behavior as a team. In order to function effectively or optimally as a team it may be necessary that the individual members are capable of perceiving affordances for the team. On the other hand, it may be the case that team members only need to perceive affordances for other individual teammates, rather than perceiving affordances for joint action, and adjust their own actions accordingly so as to produce the desired, coordinated outcome for the team. Empirical studies that can differentiate among those two possible roles of affordance perception in relation to teamwork may provide useful data for improving performance in team sports.

Perceiving Affordances of Other People. Other people offer perceivers opportunities for action. For example, in basketball, a teammate may afford allowing me to separate myself from my defender by setting a pick for me, or an opponent may be defendable. As is the case with perceiving affordances for joint action, very little research has examined the perception of what other people afford. In an intriguing set of studies the affordance of whether a person affords mugging has been studied using point-light displays that depicted the person walking (Gunns, Johnston, & Hudson, 2002; Johnston, Hudson, Richardson, Gunns, & Garner, 2004). Those studies revealed that information contained in the kinematics of walking were informative of the walker's vulnerability to a criminal attack.

CONCLUSIONS

Athletes are routinely confronted with enormously complex situations that they typically handle with seeming ease and grace. A viable theory of perception and action must explain how an actor performs successfully more often than not when confronted with complex tasks such as those encountered on the athletic field. Consider a forward in soccer dribbling the ball up the field. The forward is confronted with an almost innumerable array of possible actions. The forward could shoot, pass to an open teammate, pass to a less open teammate but one who is in a position to score, continue to dribble upfield (choosing a path based on the position, movement, and spacing of defenders, and the defenders' ability to close the gap), etc. The forward must determine what actions are possible, determine from among those actions which are most likely to be successful given the existing constraints, and then select from among a dynamic flux of optical variables those invariant features of stimulation that will allow for the successful guidance of the desired behavior. All of that occurs within periods of time ranging from mere milliseconds to a few seconds, and while concurrently overcoming the incredibly challenging biomechanical and neuromuscular problems associated with maintaining an upright posture while locomoting at a relatively high rate of speed while dribbling the ball with the feet.

It is apparent when considering what an athlete accomplishes in even a routine play that perception-action at this level exemplifies a very sophisticated form of "knowing about" (Turvey & Shaw, 1995). In the language used by Turvey and Shaw in their discussion of the fundamentally cognitive nature of perception and action, affordances could be said to provide a *functional semantics* for sport. In other words, affordances are a way of describing the meaning of the environment to the actor (i.e., semantics) in terms of how the actor can behave in the environment—the meaning of the environment is said to be functional because the meaning of the environment is with reference to how the actor can behave. An actor must orient and control activity with respect to behavioral possibilities of the environment, not merely to action-neutral physical properties of the environment. Physical descriptors of objects and surfaces in the environment, such as distance, speed, or height, each measured in conventional (and arbitrary) units, do not, in and of themselves, have any meaning for the actor. Affordances, in contrast, are meaningful and provide the athlete with information about how to control activity so as to achieve behavioral goals. Fleshing out the functional semantics provided by affordances will, we believe, provide insights into perception-action that are bound to have profound implications for sport. At the same time, research on affordances in sport is bound to have a profound impact on our fundamental understanding of perception and action.

REFERENCES

Adolph, K. E. (1997). *Learning in the development of infant locomotion*. Monographs of the Society for Research in Child Development, 62 (3, Serial No. 251).

Adolph, K. E., & Berger, S. A. (2006). Motor development. In W. Damon & R. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Vol 2: Cognition, perception, and language* (6th ed.) (pp. 161-213). New York: Wiley.

Ames, A. (1952). *The Ames demonstrations in perception*. New York: Hafner Publishing.

Araújo, D., Davids, K., Bennett, Simon J., Button, C., & Chapman, G. (2004). Emergence of sport skills under constraints. In A. M. Williams & N. J. Hodges (Eds.), *Skill acquisition in sport: Research, theory, and practice* (pp. 409-433). London: Routledge.

Baron, R. M., & Boudreau, L. A. (1987). An ecological perspective on integrating personality and social psychology. *Journal of Personality and Social Psychology*, *53*, 1222-1228.

Baron, R. M., & Misovich, S. J. (1993). Dispositional knowing from an ecological perspective. *Personality and Social Psychology Bulletin*, *19*, 541-552.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*, 557-660.

Bootsma, R. J. (1991). Predictive information and the control of action: What you see is what you get. *International Journal of Sports Psychology, 22*, 271-278.

Bootsma, R. J., & Peper, L. (1992). Predictive visual information sources for the regulation of action with special emphasis on hitting and catching. In L. E. Proteau (Ed.), *Vision and motor control* (pp. 285-314). Amsterdam: Elsevier.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. C. (2000). Travel broadens the mind. *Infancy*, *1*, 149–219.

Carello, C. C., & Turvey, M. T. (2000). Rotational dynamics and dynamic touch. In M. Heller (Ed.), *Touch, representation, and blindness* (pp. 27-66). Oxford: Oxford University Press.

Carello, C., Grosofsky, A., Reichel, F. D., Solomon, H. Y., & Turvey, M. T. (1989). Visually perceiving what is reachable. *Ecological Psychology, 1*, 27-54.

Cesari, P., Formenti, F., & Olivato, P. (2003). A common perceptual parameter for stair climbing for children, young and old adults. *Human Movement Science*, 22, 111-124.

Cornus, S., Montagne, G., & Laurent, M. (1999). Perception of a stepping-across affordance. *Ecological Psychology*, *11*, 249-267.

DeLucia, P. R. (1991). Pictorial and motion-based information for depth perception. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 738-748.

DeLucia, P. R., & Warren, R. (1994). Pictorial 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.

Fajen, B. R. (2005a). Calibration, information, and control strategies for braking to avoid a collision. *Journal of Experimental Psychology: Human Perception and Performance, 31*(3), 480-501.

Fajen, B. R. (2005b). Perceiving possibilities for action: On the sufficiency of perceptual learning and calibration for the visual guidance of action. *Perception, 34*(6), 741-755.

Fajen, B. R. (2005c). The scaling of information to action in visually guided braking. *Journal of Experimental Psychology: Human Perception and Performance, 31*(5).

Fajen, B. R. (under review-a). Affordance-based control of visually guided action. *Ecological Psychology*.

Fajen, B. R. (under review-b). Rapid recalibration based on optic flow in visually guided action. *Experimental Brain Research*.

Fajen, B. R., & Devaney, M. C. (2006). Learning to control collisions: The role of perceptual attunement and action boundaries. *Journal of Experimental Psychology: Human Perception and Performance*, 32(3), 300-313.

Fitzpatrick, P., Carello, C., Schmidt, R. C., & Corey, D. (1994). Haptic and visual perception of an affordance for upright posture. *Ecological Psychology*, *6*, 265-287.

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

Gibson, J. J. (1977). The theory of affordances. In R. E. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: Toward an ecological psychology* (pp. 67-82). Hillsdale, NJ: Lawrence Erlbaum Associates.

Gibson, J. J. (1986). *The ecological approach to visual perception*. Hillsdale, NJ: Erlbaum.

Gibson, J. J., & Crooks, L. E. (1938). A theoretical field-analysis of automobile-driving. *American Journal of Psychology*, *51*, 453-471.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20*, 1–19.

Gray, R., & Sieffert, R. (2005). Different strategies for using motion-in-depth information in catching. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 1004-1022.

Gunns, R. E., Johnston, L., & Hudson, S. M. (2002). Victim selection and kinematics: A point-light investigation of vulnerability to attack. *Journal of Nonverbal Behavior, 26*, 129-158.

Harris, J. M., & Dean, P. J. A. (2003). Accuracy and precision of binocular 3-D motion perception. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 869-881.

Harris, J. M., & Drga, V. F. (2005). Using visual direction in three-dimensional motion perception. *Nature Neuroscience, 8*, 229-233.

Hecht, H., & Savelsbergh, G. (Eds.). (2004). *Time-to-contact*. Amsterdam: Elsevier.

Helmholtz, H. von (1867/1925). *Treatise on physiological optics* (from 3rd German edition, Trans.) (3rd ed., Vol. III). New York: Dover.

Hove, P., Riley, M. A., & Shockley, K. (2006). Perceiving affordances of hockey sticks by dynamic touch. *Ecological Psychology*, *18*, 163-189.

Huettel, S., Polger, T., & Riley, M. A. (2003). In favor of an ecological account of color. *Behavioral & Brain Sciences*, *26*, 33.

Isenhower, R. W., Marsh, K. L., Carello, C., Baron, R. M., & Richardson, M. J. (2005). The specificity of intrapersonal and interpersonal affordance boundaries: Intrinsic vs. exrinsic metrics. In H. Heft & K. L. Marsh (Eds.), *Studies in perception & action VIII* (pp. 54-58). Mahwah, NJ: Lawrence Erlbaum Associates.

Jacobs, D. M., & Michaels, C. F. (2006). Lateral interception I: Operative optical variables, attunement, and calibration. *Journal of Experimental Psychology:Human Perception and Performance, 32*, 443-458.

Jacobs, D. M., Runeson, S., & Michaels, C. F. (2001). Learning to visually perceive the relative mass of colliding balls in globally and locally constrained task ecologies. *Journal of Experimental Psychology-Human Perception and Performance, 27*(5), 1019-1038.

Johnston, L., Hudson, S. M., Richardson, M. J., Gunns, R. E., & Garner, M. (2004). Changing kinematics as a means of reducing vulnerability to attack. *Journal of Applied Social Psychology*, *34*, 514–537.

Jones, K. S. (2003). What is an affordance? *Ecological Psychology*, *15*, 107-114.

Kim, N-G., & Turvey, M. T. (1998). Optical flow fields and Bernstein's "modeling of the future." In M. L. Latash (Ed.), *Bernstein's traditions in motor control* (pp. 221-265). Hillsdale, NJ: Erlbaum.

Kirsh, D. (1991). Foundations of AI: The big issues. *Artificial Intelligence*, *47*, 3-30.

Konczak, J., Meeuwsen, H. J., & Cress, E. M. (1992). Changing affordances in stair climbing: The perception of maximum climbability in young and old adults. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 691-697.

Lee, D. N. (1974). Visual information during locomotion. In R. B. MacLeod & J. H. L. Pick (Eds.), *Perception: Essays in honor of James J. Gibson* (pp. 250-267). Ithaca, NY: Cornell University Press.

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

Lee, D. N. (1980). Visuo-motor coordination in space-time. In G. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 281-293). Amsterdam: North-Holland.

Lee, D. N., & Lishman, R. (1977). Visual control of locomotion. *Scandinavian Journal of Psychology, 18*, 224-230.

Lee, D. N., & Reddish, P. E. (1981). Plummeting Gannets - a Paradigm of Ecological Optics. *Nature, 293*(5830), 293-294.

Lee, D. N., Davies, M. N. O., Green, P. R., & van der Weel, F. R. (1993). Visual control of velocity of approach by pigeons when landing. *Journal of Experimental Biology, 180*, 85-104.

Lee, D. N., Reddish, P. E., & Rand, D. T. (1991). Aerial docking by Hummingbirds. *Naturewissenschaften, 78*, 526-527.

Lee, D. N., Simmons, J. A., Saillant, P. A., & Bouffard, F. (1995). Steering by echolocation: a paradigm of ecological acoustics. *Journal of Comparative Physiology [A], 176*, 347-354.

Lee, D. N., Young, M. F., Reddish, P. E., Lough, S., & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology: A, 35A*, 333-346.

Lombardo, T. (1987). *The reciprocity of perceiver and environment: The evolution of James J Gibson's ecological psychology*. Hillsdale, NJ: Erlbaum.

Mark, L. S., Balliett, J. A., Craver, K. D., Douglas, S. D., & Fox, T. (1990). What an actor must do in order to perceive the affordance for sitting. *Ecological Psychology, 2*, 325-366.

Mark, L. S., Nemeth, K., Gardner, D., Dainoff, M. J., Paasche, J., Duffy, M., & Grandt, K. (1997). Postural dynamics and the preferred critical boundary for visually guided reaching. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1-15.

Mark, L.S. (1987). Eye-height scaled information about affordances: A study of sitting and stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 360-370.

Marsh, K. L., Richardson, M. J., Baron, R. M., & Schmidt, R. C. (2006). Contrasting approaches to perceiving and acting with others. *Ecological Psychology*, *18*, 1-38.

McArthur, L. Z., & Baron, R. M. (1983). Toward an ecological theory of social perception. *Journal of Personality and Social Psychology*, *90*, 215-238.

Michaels, C. F. (2003). Affordances: Four points of debate. *Ecological Psychology, 15*, 135-148.

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

Michaels, C. F., & de Vries, M. M. (1998). Higher order and lower order variables in the visual perception of relative pulling force. *Journal of Experimental Psychology: Human Perception and Performance, 24*(2), 526-546.

Michaels, C. F., Zeinstra, E. B., & Oudejans, R. R. (2001). Information and action in punching a falling ball. *Quarterly Journal of Experimental Psychology: A, 54*, 69-93.

Müller, J. (1842). *Handbuch der Physiologie des Menschen* [Handbook of human physiology] (Vols. 1 and 2). London: Taylor and Walton. (Original work published 1833-1840)

Norman, D. A. (1988). *The psychology of everyday things*. New York: Basic Books.

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*(4), 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 and Performance, 20*, 591-612.

Pepping, G. J., & Li, F. X. (1997). Perceiving action boundaries in the volleyball block. In S. M. A. Schmuckler & J. M. Kennedy (Eds.), *Studies in perception and action IV* (pp. 137-140). Mahwah, NJ: Lawrence Erlbaum Associates.

Pepping, G. J., & Li, F. X. (2000). Changing action capabilities and the perception of affordances. *Journal of Human Movement Studies, 39*, 115-140.

Ramenzoni, V. C., Riley, M. A., Davis, T., & Snyder, J. (2005). Perceiving whether or not another person can use a step to reach an object. In H. Heft & K.L. Marsh (Eds.), *Studies in perception and action VIII* (pp. 15-18). Mahwah, NJ: Erlbaum.

Ramenzoni, V. C., Riley, M. A., Shockley, K., & Davis, T. (2006). An information-based approach to action understanding. *Manuscript submitted for publication*.

Regan, D. (1997). Visual factors in hitting and catching. *Journal of Sports Sciences, 15*(6), 533-558.

Regan, D., & Gray, R. (2000). Visually guided collision avoidance and collision achievement. *Trends in Cognitive Sciences, 4*, 99-107.

Regan, D., & Kaushal, S. (1994). Monocular Discrimination of the Direction of Motion in-Depth. *Vision Research, 34*(2), 163-177.

Richardson, M. J., Marsh, K. L., & Baron, R. M. (in press). Judging and actualizing intrapersonal and interpersonal affordances. *Journal of Experimental Psychology: Human Perception and Performance*.

Rochat, P. (1995). Perceived reachability for self and for others by 3- to 5-year old children and adults. *Journal of Experimental Child Psychology*, *59*, 317-333.

Rochat, P., & Wraga, M. (1997). An account of the systematic error in judging what is reach-able. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 199-212.

Runeson, S. (1988). The Distorted Room Illusion, Equivalent Configurations, and the Specificity of Static Optic Arrays. *Journal of Experimental Psychology-Human Perception and Performance, 14*, 295-304.

Rushton, S. K., & Wann, J. P. (1999). Weighted combination of size and disparity: a computational model for timing a ball catch. *Nature Neuroscience, 2*, 186-190.

Savelsbergh, G. J., Whiting, H. T., & Bootsma, R. J. (1991). Grasping tau. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 315-322.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences*, *10*, 70-76.

Sedgwick, H. A. (1980). The geometry of spatial layout in pictorial representation. In M. Hagen (Ed.), *The perception of pictures VI* (pp. 33-90). New York: Academic Press.

Sedgwick, H.A. (1973). *The visible horizon: A potential source of visual information for the perception of size and distance*. Unpublished doctoral dissertation, Cornell University, Ithaca, NY.

Shaw, R. E., Turvey, M. T., & Mace, W. M. (1982). Ecological psychology: The consequences of a commitment to realism. In W. Weimer & D. Palermo (Eds.), *Cognition and the symbolic processes II* (pp. 159-177). Hillsdale, NJ: Erlbaum.

Smith, M. R., Flach, J. M., Dittman, S. M., & Stanard, T. (2001). Monocular optical constraints on collision control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 395-410.

Solomon, H. Y., & Turvey, M. T. (1988). Haptically perceiving the distances reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 404-427.

Stoffregen, T. A. (2003). Affordances as properties of the animal-environment system. *Ecological Psychology, 15*, 115-134.

Stoffregen, T. A., Gorday, K. M., Sheng, Y-Y., & Flynn, S. B. (1999). Perceiving affordances for another person's actions. *Journal of Experimental Psychology: Human Perception & Performance, 25*, 120-136.

Tresilian, J. R. (1997). Revised tau hypothesis: A consideration of Wann's (1996) analyses. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1272-1281.

Tresilian, J. R. (1999). Visually timed action: Time-out for 'tau'? *Trends in Cognitive Sciences, 3*, 301-309.

Turvey, M. T. (1975). Perspectives in vision: Conception or perception? In D. Duane & M. Rawson (Eds.), *Reading, perception, and language* (pp. 131-194)

Turvey, M. T. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*, *4*, 173-187.

Turvey, M. T. (2004). Space (and its perception): The first and final frontier. *Ecological Psychology*, *16*, 25-29.

Turvey, M. T., & Shaw, R. E. (1995). Toward an ecological physics and a physical psychology. In R. Solso & D. Massaro (Eds.), *The science of the mind: 2001 and beyond* (pp. 144-169). Oxford: Oxford University Press.

Turvey, M. T., & Shaw, R. E. (1999). Ecological foundations of cognition: I. Symmetry and specificity of animal-environment systems. *Journal of Consciousness Studies*, *6*, 95-110.

Turvey, M. T., Shaw, R. E., Reed, E. S., & Mace, W. M. (1981). Ecological laws of perceiving and acting: In reply to Fodor and Pylyshyn (1981). *Cognition*, *9*, 237-304.

Tyldesley, D. A., & Whiting, H. T. (1975). Operational timing. *Journal of Human Movement Studies, 1*, 172-177.

van der Kamp, J., Savelsbergh, G. J., & Smeets, J. (1997). Multiple information sources in interceptive timing. *Human Movement Science, 16*, 787-821.

van der Meer, A. L. H. (1997). Visual guidance of passing under a barrier. *Early Development and Parenting*, *6*, 149-157.

Vera, A. H., & Simon, H. A. (1993). Situated action: A symbolic interpretation. *Cognitive Science*, *17*, 7-48.

Wagner, H. (1982). Flow-field variables trigger landing in flies. *Nature, 297*, 147-148.

Wann, J. P. (1996). Anticipating arrival: is the tau margin a specious theory? *J Exp Psychol Hum Percept Perform, 22*, 1031-1048.

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

Warren, W. H. (1995). Constructing an econiche. In J. Flach, P. Hancock, J. Caird, & K. Vicente (Eds.), *Global perspectives on the ecology of human-machine systems* (pp. 210-237). Hillsdale, NJ: Lawrence Erlbaum Associates.

Warren, W. H., & Whang, S. (1987). Visual guidance of walking through apertures: Body-scaled information for affordances. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 371-383.

White, E., & Shockley, K. (2005, July). Perceiving pass-under-ability while walking and sitting. Paper presented at the 13th International Conference on Perception and Action, Monterey, CA.

Williams, A. M., Davids, K., & Williams, J. G. (1999). *Visual perception and action in sport*. London: E & FN Spon.

Wraga, M. (1999). The role of eye height in perceiving affordances and object dimensions. *Perception & Psychophysics, 61*, 490-507.

Zaff, B. (1989). *Perceiving affordances for oneself and others: Studies in reaching and grasping*. Unpublished doctoral dissertation, Ohio State University, Columbus, Ohio.

Zaff, B. (1995). Designing with affordances in mind. In J. Flach, P. Hancock, J. Caird, & K. Vicente (Eds.), *Global perspectives on the ecology of human-machine systems* (pp. 238-272). Hillsdale, NJ: Lawrence Erlbaum.

Zago, M., & Lacquaniti, F. (2005). Visual perception and interception of falling objects: a review of evidence for an internal model of gravity. *Journal of Neural Engineering, 2*, S198-S208.

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