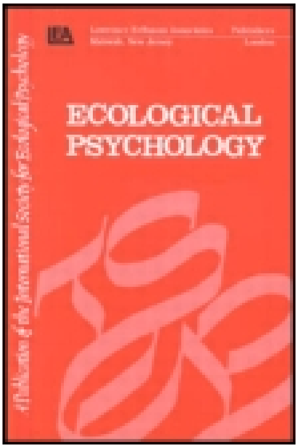

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Affordances as Probabilistic Functions: Implications for Development, Perception, and Decisions for Action

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Affordances as Probabilistic Functions: Implications for Development, Perception, and Decisions for Action

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We propose a new way to describe affordances for action. Previous characterizations of affordances treat action possibilities as binary categories—either possible or impossible—separated by a critical point. Here, we show that affordances are probabilistic functions, thus accounting for variability in motor performance. By measuring an affordance function, researchers can describe the likelihood of success for every unit of the environment. We demonstrate how to fit an affordance function to performance data using established psychophysical procedures and illustrate how the threshold and variability parameters describe different possibilities for action. Finally, we discuss the implications of probabilistic affordances for development, perception, and decision making.

Affordances are possibilities for action. Actions are possible or not depending on the current fit between the features of the body and the properties of the environment. Motor learning and development involve a process of expanding affordances and acquiring new possibilities for action. Affordances are central to Gibson's (1979/1986) ecological approach to perception because a primary role of perception is to guide action adaptively by generating and detecting information to specify affordances. Thus, to correctly characterize the problem for perceptual systems and to focus research on the specifying information for affordances, we must correctly characterize affordances.

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Here, we propose a new way of characterizing affordances. Rather than defining affordances in terms of a critical point dividing possible from impossible actions (e.g., Warren, 1984; Warren & Whang, 1987), we suggest that affordances are better considered as continuous, probabilistic functions that represent an individual's likelihood of successful performance across a range of environmental increments. We describe how established procedures in psychophysics can be adapted to estimate affordance functions and argue that these procedures provide advantages over extant methods. Finally, we discuss the implications of probabilistic affordance functions for understanding motor learning and development and for informing research on perception of affordances.

PREVIOUS WORK

A shortcut method of characterizing affordances is to assume group differences in affordances without measuring people's performance in the task. Grouping people based on gross differences in their bodies (tall vs. short, broad vs. narrow shoulders) provides a crude way of assessing whether perceptual judgments scale to affordances (Stefanucci & Geuss, 2009; Wagman & Malek, 2008, 2009). Presumably, taller people require higher overhead clearance for passage than shorter people and those with broader shoulders require wider openings for passage than those with narrower shoulders; perceptual judgments should reflect those differences.

But to test whether an individual's perceptual judgments scale to that individual's possibilities for action, researchers must measure each person's ability in the task. To do this, researchers typically identify a transition point that marks the boundary at which an action shifts from possible to impossible—termed a *critical point* (Mark, 1987; Warren, 1984; Warren & Whang, 1987) or *affordance threshold* (Franchak, Celano, & Adolph, 2012; Franchak, van der Zalm, & Adolph, 2010; Ishak, Adolph, & Lin, 2008). Individual assessment of affordances is widespread, but formal definitions of critical points vary greatly, muddling comparisons across studies and confusing our understanding of affordances. Some researchers define critical points as the upper or lower limit of performance: smallest doorway allowing passage (Warren & Whang, 1987), highest barrier inducing ducking (van der Meer, 1997), largest riser height for stair climbing (Mark, 1987), or highest barrier for stepping over (Kingsnorth & Schmuckler, 2000). However, using best (or worst) performance as the metric for affordances is problematic because it describes the extremes of performance, not necessarily what people can do consistently. Other researchers define critical points as the cutoff point marking success on some proportion of trials: lowest barrier walked under on 50% of trials (Stefanucci & Geuss, 2010), narrowest doorway squeezed through on 67% of trials (Franchak & Adolph, 2012), largest drop-off or steepest slope descended on 67% or 75% of trials (Adolph, 1995; Adolph & Avolio, 2000; Kretch & Adolph, 2013), and so on. Although the cutoff method locates the affordance threshold between upper and lower limits, the performance criterion is arbitrary.

AFFORDANCES AS ACTION CATEGORIES VERSUS PROBABILISTIC FUNCTIONS

Critical points are a convenient, albeit arbitrary, way of characterizing affordances. However, the notion of a critical point implies that affordances are action categories (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Warren, 1984; Warren & Whang, 1987): the action is possible for some range of increments and impossible for an adjoining range, with the affordance threshold as the boundary that divides the two categories (Figure 1A). But whether affordances are categorical is an empirical question. Given the same environment, action categories make sense only if performance is highly consistent. To the extent that performance is variable across repeated trials at the same increment, affordances are not categorical. Performance variability is largely ignored in affordance research (but see Franchak et al., 2012), but variable performance is well documented in research on motor control (Bernstein, 1967; Slifkin &

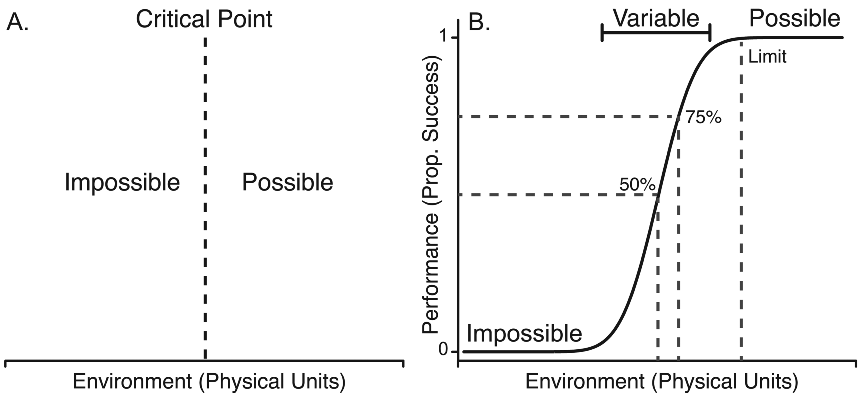

FIGURE 1 Affordances depicted as (A) action categories versus (B) probabilistic functions. (A) The critical point divides the environment into regions where actions are possible or impossible. (B) The affordance function describes the probability of success for every unit of the environment. On the tails of the function, the action is either possible or impossible. Success is variable along the inflection of the curve. Gray dashed lines show how different threshold definitions are related by the affordance function.

Newell, 1998). Actions cannot be performed exactly the same way repeatedly, and some actions are more variable than others; as a consequence, success and failure can vary probabilistically.

Modeling affordances as probabilistic functions addresses the variable nature of action performance. Rather than dividing the environment into categories of success and failure, a continuous function represents the probability of success at each unit of the environment (Figure 1B). Instead of choosing an arbitrary critical point to characterize affordances, the continuous function includes every point: Figure 1B shows how the 50% threshold, 75% threshold, and limits of performance are described by a single function. The shape of the function represents variability in performance. If the function has a very shallow slope (as in Figure 1B), there is a significant range of the environment over which performance is variable. If the function has a very steep slope (approximating a step function), then the affordance is essentially categorical. By measuring the shape of the affordance function, the extent to which affordances are categorical or probabilistic can be determined empirically.

THE AFFORDANCE FUNCTION

Figure 2 illustrates the affordance function and associated parameters with data from two people walking through openings that varied in width. The affordance function, like other psychophysical functions, relates a physical variable to a performance variable. In our example, the physical variable is the width of the opening in centimeters, and the performance variable is the rate of successful passage. The bounds of the physical variable are dictated by the environment. Openings can range from 0 (no opening) to infinitely wide. Other environmental variables have different ranges of possible values; for example, slant of the ground can range from 0° to 90°. In principle, performance, expressed as the rate of success, must be restricted in range from 0 (always fail) to 1 (always succeed). In practice, researchers can present a unit of the environment at which consistent failure is guaranteed, but the upper asymptote of consistent success depends on the task and the actor's skill level; novice infant walkers, for example, may not achieve consistent success at walking down even the shallowest of slopes because they struggle to keep balance on flat ground.

The symbols in Figure 2 denote the rate of success at each opening size for two participants. Affordance functions are fit to the data. Here, we fit a cumulative Gaussian probability density function using maximum likelihood estimates for the mean and variance. Methods for fitting psychometric functions are discussed extensively elsewhere (Kingdom & Prins, 2010; Wichmann & Hill, 2001). For walking through openings, success becomes more likely as openings become larger, so the function increases from left to right. For other actions,

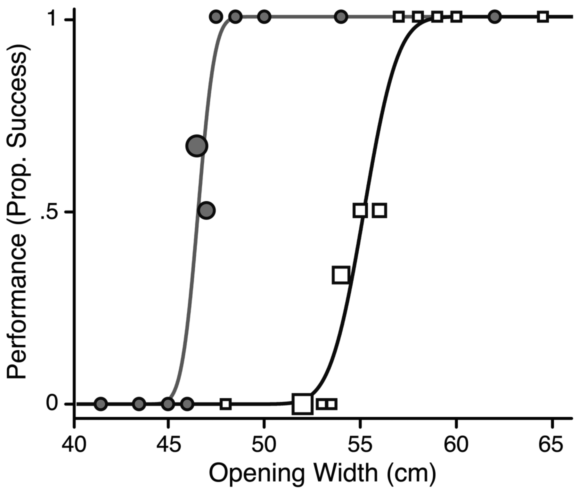

FIGURE 2 Affordance functions for a narrow-shouldered woman (gray line) and broad-shouldered man (black line) walking through doorways. Gray circles and black squares denote the proportion of trials each participant walked straight through the opening without turning; relative symbol size represents the number of trials completed at each increment.

the probability of success may decrease as the environmental variable increases (e.g., walking down slopes or over drop-offs becomes less possible as surface slant and drop-off height increase).

Although we used a cumulative Gaussian function in our example, other functions could also be used to model affordance data including the exponential, Weibull, and log-normal. Different affordances may be best described by very different functions: an affordance that does not depend on the physical variable on the x-axis should resemble a uniform distribution—that is, the action has a fixed probability of success at every level of the variable.

For the Gaussian model, the mean denotes the center point of the function, that is, where performance is 50%. The gray curve in Figure 2 is centered on 46.6 cm, meaning that the participant can navigate a 46.6-cm opening without turning the shoulders on 50% of attempts. We refer to the mean as the affordance threshold because it marks the point where success transitions from less to more probable. Different thresholds move the function to different locations, left to right, along the x-axis. Compare the two curves in Figure 2: the gray curve represents a fit to data from a narrow-shouldered woman and the black curve is fit to data from a broad-shouldered man. The man requires more space for passage; his affordance threshold is larger (55.2 cm), and his function shifts rightward along the x-axis.

The variance parameter determines the spread of the function. When variability is large, the function has a gradual slope, and the inflection of the curve covers a wide range of increments. When the variability is small, the curve has a steep slope, and the inflection of the curve is narrow. Both curves in Figure 2 have inflections that cover a range of increments, indicating that possibilities for passage were not categorical. The variance of the narrow-shouldered woman is 0.7 cm, half the variance of the broad-shouldered man (1.4 cm), indicating that she performed more consistently from trial to trial. Differences in variability highlight one problem that arises when critical points are defined by the extremes of performance: The best performance of a variable participant is farther from mean performance than that of a consistent participant. In other words, critical points based on extremes are not comparable across participants, groups, or tasks where variability differs.

Other parameters are available in the Gaussian model and similar models. For example, a newly walking infant may not be able to successfully walk a slope of any steepness 100% of the time; the function might start at 80% success for walking over flat ground and then decrease as slant increases. Researchers might also consider fitting multivariate functions that describe the probability of success as a function of two or more physical variables: for example, consider the changing probability of walking down slopes as both the slant and the friction are varied, or the changing probability of tossing a ball into a basket as both the distance and size of basket are varied.

Finally, there are methodological considerations one must consider when fitting psychophysical functions. To yield good estimates of the shape of the function, one must collect sufficient data along the inflection of the curve. Suppose the real probability of success at a given opening size is 20%. If the participant only receives two trials at that opening, the only possible success rates are 0, 50%, and 100%. More trials are needed to have the possibility of measuring 20% performance. A common practice in affordance studies is to use the method of constant stimuli to present participants with three or four trials at a range of widely spaced increments (Higuchi, Cinelli, Greig, & Patla, 2006; Stefanucci & Geuss, 2010). Others use the method of limits to arrive at an estimate of the critical point (Mark, 1987; Warren & Whang, 1987). However, both methods spread trials across too broad a range of increments to yield a good estimate of variability. Adaptive psychophysical procedures can be used to quickly find a participant's threshold and then focus trials around the area of interest (Cornsweet, 1962; Kingdom & Prins, 2010; for examples, see Adolph, 1995; Franchak & Adolph, 2012; Franchak et al., 2012). Furthermore, the size of the spacing between levels of the environment—the sampling frequency—can limit the accuracy of finding the threshold and variability. For example, if performance varies across a 2-cm range of openings, presenting openings in 5-cm increments will not allow for an accurate estimate of the affordance function.

IMPLICATIONS FOR DEVELOPMENT AND SKILL ACQUISITION

What are the effects of development on motor performance? Measuring affordance functions over time reveals developmental changes in individuals' motor performance. But simply knowing how performance changes over time does not speak to the process of change. Measuring other time-varying factors, like body dimensions and experience, can help to identify which developmental factors affect motor performance and skill acquisition.

Figure 3 shows weekly changes in one woman's ability to fit through doorways over the course of pregnancy and after giving birth (Franchak & Adolph, 2013): the affordance threshold increased over pregnancy and decreased postpartum (white squares), but variability remained unchanged (white circles). Also

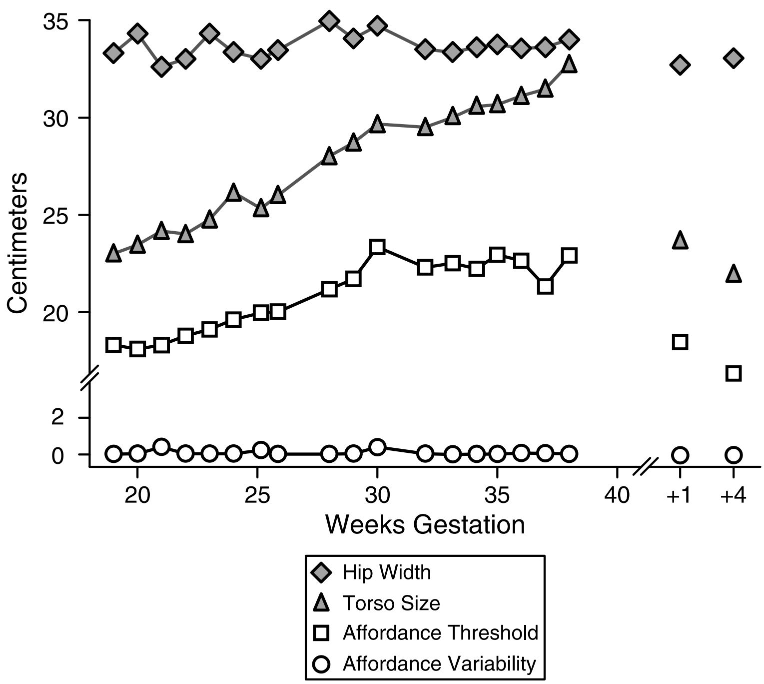

FIGURE 3 Developmental change in body dimensions and affordance parameters for a pregnant woman squeezing through doorways. Body width measured at the hips (gray diamonds) remained unchanged, but sagittal torso size measured from the back to the navel (gray triangles) increased over weeks of pregnancy. Affordance thresholds (white squares) increased with growth over pregnancy and decreased after delivery, but variability parameters (white circles) did not change.

plotted are changes in body width at the hips (gray diamonds) and sagittal torso size (gray triangles, measured from the back to the navel). Of the two, sagittal torso size is the body dimension that best predicts affordance thresholds because the woman turned to the side to squeeze through; were she to walk straight through, hip dimensions would be more relevant. However, affordance thresholds are smaller than torso size at each session, indicating that she compressed her body while squeezing through openings. For safety reasons, we did not measure pregnant women's compressed body dimensions. However, in other work we found that younger and older (nonpregnant) adults' torsos compress by 3–4 cm, and measurements of compressed body size closely match affordance thresholds (Comalli, Franchak, Char, & Adolph, 2013).

It is not always feasible to measure changes in individuals longitudinally. For example, comparing performance of infants, children, and adults warrants a cross-sectional approach. Figure 4 shows affordance thresholds and variability parameters of 16-, 22-, and 32-month-olds; 5- and 7-year-olds; and adults for fitting their hands through diamond-shaped apertures of varying size (Ishak, Franchak, & Adolph, 2014). Affordance thresholds increased with age (shown by symbol shading) but hand width is the best predictor ($R^2 = .64$). The bottom panel of Figure 4 shows that variability parameters were small and did not change with age or hand size ($R^2s < .027$). Note the considerable overlap in hand width and affordance thresholds between members of different age groups. Although hand width strongly predicts affordance thresholds, there is still considerable unexplained variance. The dynamics of hand configuration likely explain the imperfect scaling between static hand size and thresholds: When reaching through openings, people configure their hands in different ways to make them smaller. Scrunched hand width strongly correlates with affordance thresholds in adults (Ishak et al., 2008), but we could not measure scrunched hand size in infants and young children. Changes in affordance thresholds for fitting through doorways and reaching through openings show developmental changes that depend on body growth, but they also reveal important new insights: dynamic aspects of the body, not static dimensions, determine affordances (see also Fajen, 2005, 2007).

Moreover, many developmental changes in motor abilities are not the result of changes in body size. Balance and strength, for example, also improve with age and experience and affect motor performance. We culled data from six studies of infants walking down slopes (Adolph, 1995, 1997; Adolph & Avolio, 2000; Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008; Gill, Adolph, & Vereijken, 2009; Tamis-LeMonda et al., 2008) and fit affordance functions to each infant's data, yielding a sample of 178 infants between 10 and 18 months of age. Although affordance thresholds are predicted by age ($R^2 = .41$), walking experience better predicts infants' abilities ($R^2 = .60$; Figure 5). One might expect that infants' performance would become more consistent with experience.

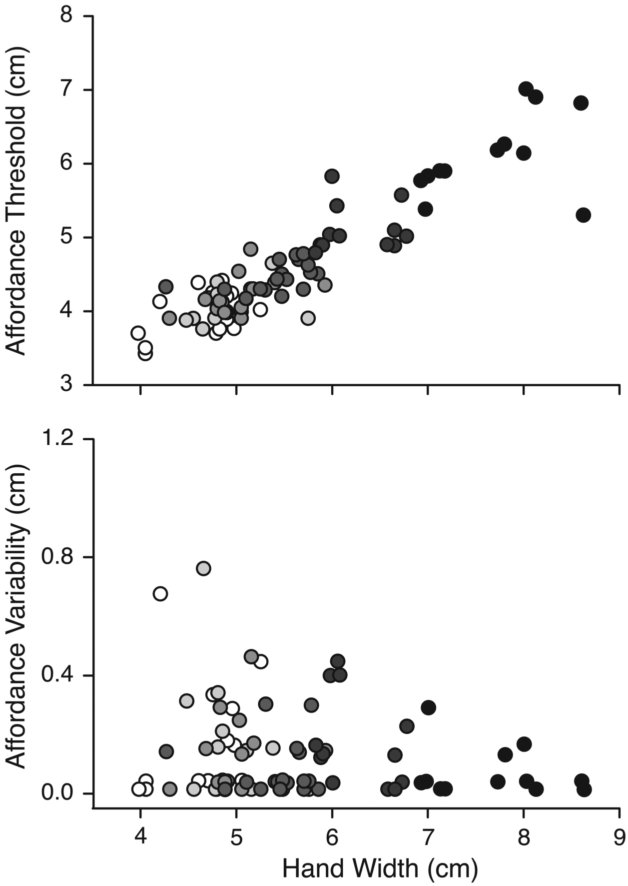

FIGURE 4 Affordance thresholds (top) and variability parameters (bottom) of 16-, 22-, and 32-month-olds; 5- and 7-year-olds; and adults fitting their hands through diamond-shaped apertures. The x-axis represents hand width in centimeters. Each symbol shows one participant. Age is depicted by symbol shading (lighter symbols = younger, darker symbols = older).

However, this was not the case. Variability of affordances varied widely among infants but did not correlate with age or experience ($R^2s < .003$), meaning that an 8° increase in slant is as challenging to an experienced walking infant as it is to a novice walker.

The tasks presented here did not show changes in the variability of affordances over development. However, affordance variability might decrease for tasks where *movement variability* decreases with experience. Many studies of skill

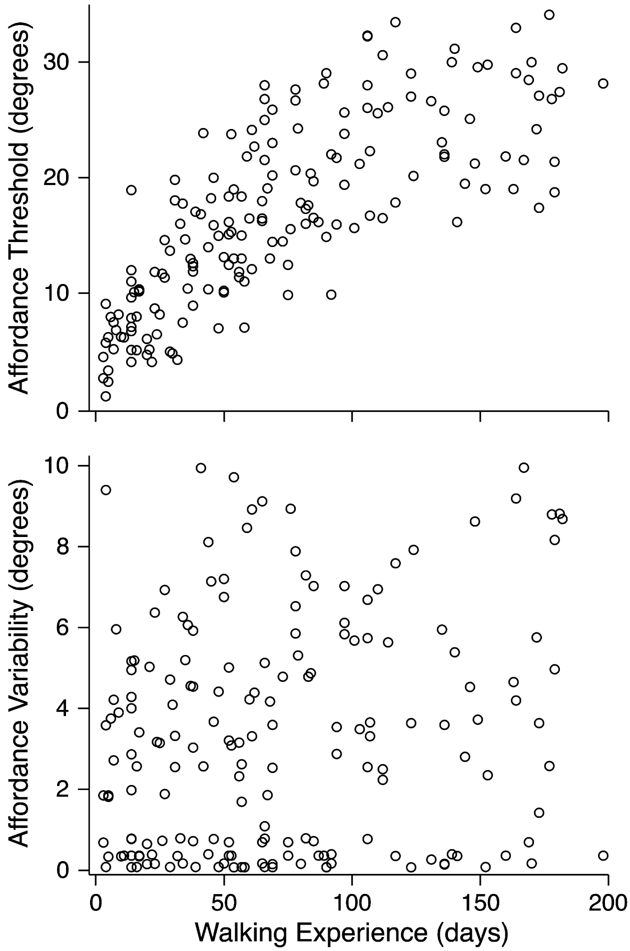

FIGURE 5 Affordance thresholds (top) and variability parameters (bottom) for 178 infants walking down slopes. The x-axis represents walking experience, measured in days since the onset of independent walking. Each symbol shows one participant.

acquisition show that variability in the kinematics of movements decreases over learning and development. For example, step-to-step variability in infant crawling and walking movements decreases with experience (Adolph, Vereijken, & Denny, 1998; Adolph, Vereijken, & Shrout, 2003). Infant reaching (Berthier & Keen, 2006) and hammering movements (Kahrs, Jung, & Lockman, 2013) become straighter and less variable with experience. Moreover, motor learning studies show that spatial variability decreases in rapid pointing (Georgopoulos, Kalaska, & Massey, 1981), target interception (Ranganathan & Newell, 2010), and grasping (Darling, Cole, & Abbs, 1988).

IMPLICATIONS FOR PERCEIVING AFFORDANCES

The affordance function is vital to understanding perception. Affordances reflect the objective truth about whether or not an action is possible, but whether an observer perceives an affordance is a separate matter. Adequately describing the affordance is paramount because it defines the problem for the perceptual system. Simply put, perception of affordances should match affordances. If affordances are action categories, then the role of the perceptual system is to discern the critical point. But if affordances are probabilistic, the problem for perception is to detect the probability of success given the current state of the environment and thus depends on the variability of the action. Greater variability flattens the inflection of the curve and increases the range over which the probability of success varies (Figure 1B). Even when variability is high, there are still regions of the environment over which the probability of success is close to 0 and 1—the tails of the function. When affordance variability is low, the affordance function approximates a step function. The inflection of the curve is very narrow and the tails of the function cover most of the environment. In such cases, perception is essentially categorical—observers need only to detect which tail of the function corresponds to the current state of the environment.

Perceptual sensitivity to affordances may be related to the underlying variability of different actions. For example, when modifying their gait to fit through openings, walkers are more variable when turning to fit through horizontal openings compared with ducking to fit under overhead barriers (Franchak et al., 2012). When verbal judgments about affordances for passage were assessed using the same curve-fitting procedure, variability for judgments about horizontal openings was greater than variability for vertical openings. Similarly, affordances for squeezing through doorways are less variable than those for navigating along ledges, and perceptual judgments for squeezing through doorways are less variable than those for navigating ledges (Comalli et al., 2013). Moreover, rapid pointing studies show that actors are sensitive to motor variability: they adjust their aim according to their individual motor variability and even adapt to artificial perturbations that increase motor noise (Trommershäuser, Gepshtein, Maloney, Landy, & Banks, 2005).

Treating affordances probabilistically also has implications for decisions about action. If affordances are considered either possible or impossible, decision making is similarly binary: actors should attempt possible actions and refuse impossible ones. But what should an actor do when the probability of success is 25%, 50%, or 95%? In these cases, we must consider the rewards for success and cost of failure. A 50% chance of success might be worth attempting if the penalty for failing is getting wedged in a doorway. But if the penalty is more severe—such as losing balance and falling—a 50% chance might not be worth attempting. Indeed, actors weigh the probability of success against the cost of errors. Seventeen-month-old infants, college-age adults, and older adults (65+ years) make more cautious decisions when navigating ledges where the penalty for errors is falling compared with fitting through doorways where the penalty for errors is entrapment (Comalli et al., 2013; Franchak & Adolph, 2012). Similarly, participants report that they would allow a greater safety margin for ducking under a barrier made of foam compared with one of metal (Wagman & Malek, 2009). When rapidly pointing to a target to win money, actors adjust their aim according to their movement variability to avoid hitting a penalty error that results in a loss of money (Trommershäuser, Maloney, & Landy, 2008).

Even in the absence of explicit penalties and rewards, variable affordances might affect the criteria for decision making. For example, success at catching fly balls depends on the speed required to run to the location where the ball will land (Fajen, Diaz, & Cramer, 2011); however, success varies from trial to trial. When reporting whether balls were catchable, participants' judgments matched their best performance rather than their threshold (50%) performance. In other words, judgments reflected what participants could do in the best circumstances rather than what they could do on average.

Finally, measuring the affordance function has consequences for understanding the perceptual information that specifies affordances. The goal of researchers is to find scale-invariant information that specifies affordances across a wide range of participants. For example, eyeheight information may specify the affordance for stepping on risers because leg length determines maximum step height and leg length is scaled to eyeheight (Mark, 1987; Warren, 1984). To that end, many studies measure affordances and judgments in terms of intrinsic units, such as the ratio of opening width to shoulder width and standing height (Higuchi et al., 2006; Higuchi et al., 2011; van der Meer, 1997; Wagman & Malek, 2008; Warren & Whang, 1987) or the ratio of riser height to leg length (Mark, 1987; Warren, 1984), on the basis that the perceptual system is detecting information scaled to those units.

In this article, we have exclusively used extrinsic units to describe affordances—centimeters to describe affordances for passing through openings and degrees to describe affordances for walking down slanting surfaces. Although we agree that intrinsic units are important for understanding the specifying information for perception, researchers' choice to only measure intrinsic units assumes rather than identifies the factors that determine a particular affordance. Prior to gathering evidence about putative intrinsic units, a more agnostic, empirical approach is to measure affordances in extrinsic units. For example, the classic work of Warren and Whang (1987) demonstrated that the affordance for walking through horizontal openings is scaled to shoulder width: narrow and broad-shouldered individuals turn to fit through openings 1.3 times their shoulder width and static shoulder width is correlated with doorway passage. But dynamic aspects of walking also play a critical role. The body sways from side to side when walking, and this lateral sway increases the spatial requirements for passage beyond the geometry of the shoulders (Franchak et al., 2012). Moreover, actors' perceptual judgments are better scaled to the actual affordance than to shoulder width, meaning that perceivers detect information that accounts for the dynamics of walking in addition to shoulder width when they judge affordances for passage. Other affordances, such as squeezing through tight spaces, also depend on dynamic aspects of the body such as compression (Comalli et al., 2013). Given that affordances depend on the characteristics of the body in motion, attempts to identify perceptual information rooted in body dynamics, such as stride length and head sway (Fath & Fajen, 2011), might be more fruitful than information based on the static geometry of the body. Furthermore, dynamic information sources may allow actors to perceive the variability of their movements, facilitating decisions that account for affordance variability. Regardless, claims about intrinsic information should be determined empirically from measuring the actual affordance.

CONCLUSION

The primary role of perception is to detect affordances, and so the starting point for research must be to understand affordances themselves. Affordances are complex relations between characteristics of the body and features of the environment. Robust, psychophysical methods can help to illuminate the relevant factors for a particular action, yielding a richer understanding of affordances and how they change over learning and development. Even simple actions like reaching and walking through openings depend on the dynamics of the body—compression, configuration, and kinematics—rather than static geometric dimensions. Movement is variable. By modeling affordances as probabilistic functions, we can account for the variable nature of action performance and systematically examine how performance variability affects perception of affordances. Future research should address how movement variability relates to affordance variability, and most important, seek an informational basis for affordances that accounts for both body dynamics and variable performance.

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