Affordances and the Ecological Approach to Throwing for Long Distances and Accuracy

Andrew D. Wilson,[1]*

Qin Zhu,[2]

&

Geoffrey P. Bingham[3]

*Corresponding author

[1] School of Social Sciences, Leeds Beckett University, Leeds UK

Email: a.d.wilson@leedsbeckett.ac.uk / DrAndrewDWilson@gmail.com

Web: https://cognitioninaction.wordpress.com/

Twitter: @PsychScientists

[2] Division of Kinesiology and Health, University of Wyoming, Laramie, WY, USA

[3] Department of Psychological and Brain Sciences, Indiana University, Bloomington, IN, USA

Introduction

All organisms are capable of producing behaviour that is exquisitely tied to their current task demands. We can quickly and effectively adapt our actions as these demands change, which matters because of the dynamic and shifting nature of our environments. We see this level of sophistication and skill in high performance situations (e.g. elite sporting activities such as the Olympics) but, if you look, you can also see it in your own day-to-day activity. We walk efficiently and effectively from place to place, effortlessly avoiding obstacles and preserving our balance. We reach and grasp for objects around us and manipulate them with great dexterity. Skilled performance is the rule, not the exception. So the big question facing psychology is, what kind of mechanism underpins this level of success? How, exactly, do we behave so effectively for so much of the time?

Skilled, functional behaviour is behaviour that forms a suitable complement to the task demands. This means that in order to understand a given behaviour, we must first understand the task it is complementing and how we come to know about it. To rephrase slightly, what properties of the environment are action relevant, and how do we perceive them? These two questions are at the heart of the ecological approach to perception and action (Gibson, 1979; Turvey, Shaw, Reed & Mace, 1981). The ecological hypothesis is that there are action relevant properties of the world called *affordances* (Gibson, 1979; Scarantino, 2003; Turvey, 1992; Turvey et al, 1981), and that we perceive these directly via *specifying information* in energy media (e.g. the optic array; Warren, 2008; the acoustic array; Gaver, 1993). Skilled behaviour emerges as we perceive these affordances and use this perception to shape our behaviour to meet their opportunities and demands.

This chapter will explain affordances and the perception of affordances in the context of *throwing for distance and accuracy*. We begin with the idea of *task dynamics* (Bingham, 1988; Bingham & Muchisky, 1995; Saltzman & Kelso, 1987) and describe how these dynamics can produce *ecological perceptual information* about themselves. We will then take a task dynamical approach to characterising and studying the affordances for throwing, which has led to numerous experiments about how humans select projectiles and launch those for distance, accuracy or both. This fascinating skill is a unique human speciality (while other animals have been known to throw, none can do so with the speed and precision of a trained human) and it has played a major part in our evolutionary success (e.g. Bingham, 1999; Calvin, 1983; Darlington, 1975; Isaac, 1987; Knusel, 1992; Martin, 2005; Meltzer, 2009; Shea, 2006). It is the perfect testbed for studying affordances and the perception of affordances, and we will review our work on these questions here. This research programme stands as a developing exemplar of the kind of research programme required to study affordances, and to therefore understand the nature of the ecological world that we perceive and act in.

We also propose for the first time here that our task dynamical affordances provide the ideal specification of 'task goal' required for modern movement variability analyses derived from the motor abundance hypothesis (Latash, 2008, 2012). There are four basic flavours of analysis; uncontrolled manifold analysis (UCM; e.g. Scholz & Schöner, 1999), stochastic optimal control theory (e.g. Todorov & Jordan, 2002), nonlinear covariation (e.g. Müller & Sternad, 2003) and the goal equivalent manifold (e.g. Cusumano & Cesari, 2006). These motor control methods evaluate movement variability with respect to a task goal, but none come with a theory about what those task goals are or how they are perceived. The ecological, perception-action, task dynamical approach to affordances is just such a theory. With all these pieces in hand, we can move towards unveiling the dynamic causal mechanisms (Bechtel & Abrahamsen, 2010; Craver, 2007) that underpin skilled, functional behaviour more generally.

Task Dynamics

Organisms produce functional behaviour by temporarily ('softly') assembling ourselves into *smart* solutions to the task at hand (Runeson, 1977). Smart solutions differ from general purpose rote solutions the way heuristics differ from algorithms; they take advantage of things which are locally true and use those as reliable shortcuts to solve particular problems, instead of trying to come up with a longer, more complex solution that can be successfully applied to all situations.

Why do we think perception-action systems are smart rather than rote? There are two reasons. First, for tasks you do often that contain reliable shortcuts, smart solutions are faster, more efficient and more stable than rote solutions (Runeson, 1976). These are good things. Second, it is often the *only* way to solve a given problem (Bingham, 1988). Human bodies have a large number of redundant degrees of freedom (Bernstein, 1967), which means that we can in principle solve a given task in many different ways. The only way to reliably pick one solution is to allow yourself to be constrained by the task dynamics, because otherwise there are too many possible ways to move and we would be frozen by indecision[1]. So you identify the task and then pick a solution, which means solutions are *task-specific*. Understanding the solution requires understanding the task.

Tasks (events involving objects and organisms in the world) unfold over time in particular ways that have to do with the composition and organisation of the event. This unfolding can only be completely characterised and uniquely identified at the level of *dynamics* (Bingham, 1995). The formal language of dynamics provides all the elements required to describe the components, the organisation of those components (in the form of a particular equation of motion), the form of the change over time (the kinematics) and the forces which caused that particular motion (the kinetics). Kinematic variables include time, position and all the temporal derivatives of position (velocity, acceleration, jerk, and so on). Kinetic variables are all of these as well as mass. A given dynamical system description of an event in the world uses some combination of these variables and arranges them in a particular way, in an equation (via addition, multiplication, and other operations). These equations then fully describe how the given event type unfolds over time and why, and setting the parameters on the variables (say, making the movement faster or slower) creates a specific instance

[1] This is a very similar motivation to Latash's motor abundance hypothesis, which is one reason why we believe task dynamical affordances will fit that framework nicely. We discuss this in more detail at the end.

of this event type. Finally, two or more dynamical systems can be coupled to each other if some of the terms in one equation reflect terms from another, and vice versa.

This gives us a principled and valid way to classify the tasks facing an organism. Two different events are different tasks if they are unfolding according to different dynamics, i.e. if they are described using different equations (different combinations and arrangements of dynamical variables). The physics of something in free fall and something being propelled are described by different equations and are thus attempts to intercept these are two different tasks. Two different events are the same task if the dynamics are the same, even if the parameters of those dynamics are different. Things fall differently on the Moon and on the Earth but this is due to varying parameters on gravity rather than the addition of an additional source of energy.

Affordances

Gibson's (1979) definition of affordances is notoriously annoying:

> *The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. (pg 119)*

There have been many attempts to cash this out more formally. Turvey et al (1981) and Turvey (1992) described them as *dispositional properties*, and Scarantino (2003) expanded and improved on this analysis thanks to Mumford's (1998) book length treatment of dispositions; see also Bingham & Muchisky (1995). Others have formalised them as relational properties created by interactions in the organism-environment system (e.g. Chemero, 2003, 2009; Rietlveld & Kiverstein, 2014; Stoffregan, 2003). These relational accounts are popular, but currently suffer from one fatal problem – none of them include a mechanism for how such relations can create information and thus be perceived.

Given the strong positive case for dispositions and the major negative against the relational accounts, we begin our analysis of affordances by treating them as dispositional properties of tasks (see Scarantino, 2003 for an excellent analysis of what this means in practice).

Affordances are the perceptible, action relevant subset of the dispositional properties of a task; tasks are defined dynamically; affordances must therefore be defined dynamically. A *dynamical task analysis* is when you characterise the task to be solved by the organism in terms of the dynamics. This can give you a finite list of candidate affordance properties to work with (Wilson & Golonka, 2013); a given task has a limited number of properties and only some of these are affordances. It's then a matter of empirical investigation to identify which properties are action relevant and therefore constitute the affordance. It is this research programme that we will elaborate on below in the context of throwing for long distances and accuracy.

The Perception of Affordances

> *The central question for the theory of affordances is not whether they exist and are real but whether information is available in ambient light for perceiving them.*
>
> *Gibson, 1979, pg 132.*

Affordances are dynamical properties of the environment. Perception must therefore be about these dynamics, but it has a problem. Perceptual systems have no direct access to these dynamics; instead, they interact with energy media such as light and these only support a kinematic projection of the dynamics (Bingham, 1988). In order to perceive a dynamical affordance, that affordance must create a kinematic pattern in an energy media that an organism can use to make perceptual contact; the pattern must be able to be used as *information* for the affordance. That information cannot be identical to the underlying dynamics, but it must specify (map 1:1 to) those dynamics.

Let's focus on the optic array for a moment, although this analysis applies to all the media perceptual systems interact with. Briefly, the interaction of light and a surface is governed by the laws of physics, which means that a given dynamical property will lead to the same optical consequences every time it occurs. There will be some variation; for example, if the light level is lower the second time the intensity of the light will be different, or you may see the world from a different vantage point. But there will still be higher order relations (*invariants-over-transformation*) that are preserved over these transformations. These invariants are, by definition, specific to the task dynamical property that created them; they map 1:1 onto the dynamics of the world. These invariants are ecological information.

Ecological information was first described in detail in Gibson (1966) and then Gibson (1979). Turvey, Shaw, Reed and Mace (1981) then formalised the ecological laws of perceiving and acting that dictate how dynamical properties are projected into, for example, light, in a way that makes the pattern informative. (Gaver (1993) has also produced an equivalent analysis for the acoustic array.) Then Frykholm & Runeson (1983) demonstrated several concrete examples of this *Kinematic Specification of Dynamics* (KSD) and showed people's perception was clearly attuned to them. There is now a variety of evidence that perception depends on these specifying patterns (e.g. Fink, Foo & Warren, 2009; Gibson, Kaplan, Reynolds & Wheeler, 1969; Kaplan, 1969; McBeath, Shaffer & Kaiser, 1995; Scholl & Tremoulet, 2000; Wilson & Bingham, 2008).

The ecological hypothesis is therefore that dynamical properties of the world can interact with energy media in such a way as to create higher-order kinematic patterns that specify those dynamics. These patterns are not identical to the world, but because of specification, they can be used by an organism to stand in for the world. If an organism detects and uses these patterns as information, it is described ecologically as perceiving the world.

The ecological research programme is therefore tasked with 1) dynamically characterising the action-relevant properties of a given task, b) kinematically characterising the information created by those properties and c) empirically testing whether organisms are using that information to perceive those dynamics. The ecological approach is doing well to the extent that the answer to (c) is 'yes'.[2]

The rest of this chapter will describe our ecological research programme that has investigated the affordances and perception of the affordances for throwing to maximum distance.

Throwing

The Task Dynamics of Throwing

Throwing is an example of projectile motion. The dynamics of projectile motion describe how an object moves through space after being given an initial push and then being left alone, other than the effects of gravity and friction (drag) - no additional propulsion. That initial push can be anything (being thrown, being shot out of a gun or cannon, being hit by a baseball bat, and so on). The trajectory of the projectile and the distance it travels depends on the object size and weight, the release height, angle and velocity, drag, air density, and gravity. The goal of the dynamics of throwing is to therefore produce a task-appropriate instance of a projectile motion.

Embodied perception-action research must always remember that it has to also analyse the task from the first person perspective of the organism (Barrett, 2011). As far as the organism is concerned, the task dynamic variables listed above must be sorted in the following way:

- *Things to be perceived*: object size, object weight, distance travelled (or distance to be travelled, in the case of targeted throwing)
- *Things to be controlled*: release height, release velocity, release angle
- *Things outside your control*: drag, air density, gravity

Implementing a given throw requires implementing the dynamics of throwing based on perceived size, weight and distance, and coupling those dynamics to the dynamics of projectile motion. You

[2] See Fajen's *affordance based control* framework for a good example of this programme in action; Fajen, (2005, 2007).

couple two dynamical systems together by having the output of one feed into the other, and sometimes vice versa. Throwing is a one way coupling, and it is achieved by having the dynamics of throwing put the body into a state you can describe with three values (release angle, release velocity and release height) which are used as parameters on the relevant variables making up the dynamics of projectile motion.

The parameters that you should choose depend on the task at hand, and the affordances that help you select the right parameters vary from task to task as well. We have so far researched three cases; throwing for maximum distance, throwing to hit a target, and throwing to inflict damage in hunting. We will now review the maximum distance data, as this is the most developed thread of the programme, and then briefly discuss the two papers relevant to targeted and impactful throwing.

Throwing for Maximum Distance

Bingham et al. (1989) began the study of affordances for throwing by examining how the human perceptual system, specifically haptic perception, is able to identify the best object for maximum distance throwing. Given objects of varying size, participants happily indicated the weight they preferred for throwing after hefting each object in their throwing hand. The preferred objects increased in weight with increasing size, and were indeed subsequently thrown the farthest by the perceivers. People were both therefore confident and accurate in their judgments. Bingham et al (1989) suggested that hefting might provide information about the affordance via a similarity between hefting and throwing dynamics and motions.

Zhu and Bingham (2008) replicated and extended these findings. They found that this affordance (size/weight/distance relation) can only be perceived by hefting with the skilled throwing hand (as opposed to elbow or foot). They also found that when they had people throw the objects, only object weight affected distance via the throwing dynamics (and then, only release speed but not release angle). Object size has its effect on maximum distance during the projectile motion. Therefore, although hefting to perceive the affordance requires perceiving both object weight and size in relation to throwing distance, only the weight directly affects the throwing motions (both size and weight affect the projectile motion). Zhu and Bingham (2008) therefore showed that Bingham's original hypothesis about how hefting provided access to the throwing affordance was incorrect; size matters for distance, but not for the throwing motion. The source of information about the affordance therefore remained unknown.

The next question concerned learning to perceive the affordance. Zhu and Bingham (2010) and Zhu, Dapena & Bingham (2009) investigated how the ability to perceive the affordance for throwing is acquired through perceptual learning. At baseline, unskilled throwers were asked to select objects for throwing and subsequently throw all objects. Their preferences were random and the preferred objects were not thrown the farthest. Hence, unskilled throwers cannot perceive the affordance for throwing.

Next, Zhu and Bingham investigated the process of learning to perceive the affordance using an experimental design to contrast two alternative hypotheses about the form of the learning. The first hypothesis was an associative process of function learning that entails both interpolation and extrapolation along the function from experienced exemplars (e.g. McDaniel & Busemeyer, 2005). This account predicted that learning and transfer would be restricted by the nature of the training set. The second hypothesis was the ecological process of becoming attuned to specifying information (e.g. Gibson, 1969; Gibson & Pick, 2000). This account predicted that learning would generalize to the entire space over which the information is defined, regardless of training set.

Unskilled throwers practiced throwing over the period of a month, with each thrower assigned to one of four groups: Group 1 threw with vision using a subset of objects of varying size but constant weight; Group 2 threw with vision using a subset of objects of varying weight but constant size; Group 3 threw with vision using a subset of objects varying in both size and weight, but of constant density; Group 4 threw without vision using the same set of objects used by Group 3. After training, all participants significantly improved throwing distances. Groups 1-3 also improved their perception of the affordance; they were now able to pick the optimal throwing object from the full set that varied in both size and weight, regardless of which set they trained with. Interestingly, throwers in Group 4 (who did not see the distance to which object were thrown during practice) did not improve on the affordance perception task until they received an extra throwing session with vision of the throw allowed. They then immediately improved on the perception task. Based on these results, Zhu and Bingham concluded that the learning process was one of attuning to information about the size-weight relation in the objects, and calibrating which specific relation to use by perceiving the distance thrown. The question remained, to what invariant did this enable the throwers to become attuned? What is the information for the size-weight relation?

The Information for the Maximum Distance Affordance

The affordance for maximum distance throwing consists of a specific relation between object sizes and weights, with larger weights for larger sizes. Bingham et al (1989) noted that the specific relation was similar to that for equal 'heaviness' according to the classic size-weight illusion. The illusion is that object weights are misperceived; equal felt heaviness requires that larger objects weigh more. Perhaps it is a specific felt heaviness that is invariant with optimality for maximum distance throws. Zhu and Bingham (2011) examined this hypothesis.

Skilled throwers were initially asked to identify the best weighted objects for throwing in various sizes. Then, among the preferred objects, either the smallest or the largest object was selected as the reference object (unbeknownst to the participants) for a judgment of equal felt heaviness. In a second task, the throwers compared the reference object with the remaining objects to judge those that felt equally heavy to the reference object. The throwers selected the same objects at each weight that they had chosen as best for throwing. The results supported the hypothesis that all objects preferred for throwing were those that felt of a specific equal heaviness. Learning the affordance entails learning about equal heaviness in the throwing context, and distance travelled must be perceived so as to pick out the specific heaviness. Once this heaviness is identified, learning can generalise across untrained objects.

In all of these studies on the affordance for throwing, it was consistently found that optimal objects for throwing increased in weight with increasing size in the same way as for equal heaviness in the size-weight illusion. Therefore, the illusion in fact has an ecological function, namely, it enables throwers to reliably detect the best object for throwing. The illusion is not an illusion or misperception of weight at all; instead, it is a functionally effective and accurate perception of an affordance (Zhu & Bingham, 2011).

Felt heaviness has been shown to vary as a function of the rotational inertia (e.g. Shockley, Carello & Turvey, 2004; see Turvey, 1996 for an overview of this notion of dynamic touch). Since the felt heaviness is also used for detecting the affordance for throwing, the obvious question was whether the rotational inertia would change the felt heaviness and thus, perception of the affordance. Zhu et al. (2013) systematically manipulated the rotational inertias of objects and asked skilled throwers to judge both throw-ability and equal heaviness while hefting the objects. The results showed that the perceived affordance for throwing did not vary with the rotational inertias; dynamic touch is not the basis of the perception of this particular affordance.

Another ecological question concerning perception of this affordance is whether the *relative* optimality of objects for throwing can be perceived. When selecting objects to throw in the world, the actually optimal object is not necessarily present; can people select the best object from a given set? Zhu, Mirich and Bingham (2014) investigated this question using a magnitude estimation task. Skilled throwers were asked to rate each object on its throw-ability by comparing it to a reference object that was previously selected as preferred for throwing. The results showed a good match between the mean magnitude estimation and mean distances of throwing, suggesting that the relative optimality objects for throwing can be detected if the optimal object is not available.

Summary

Projectiles afford throwing for maximum distance to the extent that their size-weight relation falls on a specific function. This function is one of many that describe when objects of different sizes and weights feel equally heavy to humans (the size-weight illusion). Learning to perceive the affordance requires learning the specific felt heaviness that matches the specific function that identifies objects that will travel the farthest when thrown by a human. This requires experience with variation in either size, weight or density (size and weight) plus visual perception of the distance travelled by those varied objects.

Throwing for Accuracy

The second type of throwing task is throwing to hit a target. It is the same kind of task as above because the dynamics are the same; only the parameters change. The goal of the throwing dynamics is still to produce a particular release angle, release speed and release height. However, which combination is best now depends on the target's size and location in space (distance, height and orientation) relative to the thrower, rather than the goal of maximising distance. In other words, the relevant affordance in this task, given a projectile, is the affordance of the target to be hit.

Wilson, Weightman, Bingham & Zhu (2016) had experts from three sports (male baseballers and cricketers, female softballers) throw tennis balls to hit a vertically oriented 4x4ft Perspex target. In Experiment 1, the target was set at one of three distances (5m, 10m, 15m) and three heights (centred at 1m, 1.5m, 2m; roughly eye-height +/- 0.5m). The results showed that all the experts scaled their release parameters to the target location; changes in distance led to changes in release angle and speed, while changes in height led to changes in angle. Experts liked to 'throw a rope', that is, fast and flat (this minimises flight time, often a pressure in a sporting context).

A projectile motion can also cover a given distance by flying slow and high. In a second experiment, we forced male cricket experts into this mode by changing the target orientation from vertical to horizontal and varying the distance. The experts readily changed their throwing from fast and flat to slow and high and maintained near perfect accuracy in all conditions. This remained true even under monocular viewing conditions.

To identify why throwers were choosing the release parameters that they were, we ran extensive simulations of the projectile motion of a tennis ball thrown towards our target. For each target location and orientation condition, we ran the equations within two loops, one for variation in release angle (ranging from -30° to 90°; this range emerged from the simulations as necessary to map the complete affordance structure for all target locations) and one for variation in release speed (here ranging from $0ms^{-1}$ to $45ms^{-1}$; our highest observed release speed across the two experiments reported below was $45.01ms^{-1}$). The results revealed a set of parameter combinations that led to a hit. This set changed with distance, height and orientation, and this set is the affordance of a given target to be hit by throwing. We now refer to the plots of these sets as *affordance maps* (refer to Figure 1 for an example; see Wilson et al, 2016a for all the details).

Expert performance fell into the identified sets, and variability in performance was also shaped by the form of the sets. Fast and flat throws reside in a stable location in the map for vertical targets (small errors in either speed or angle often still produce throws that lead to hits). This stability goes away when the target changes orientation and when it is horizontal the slow and high throws are in the most stable region. The target affordance analysis accounted for the expert release parameter selection nicely; they clearly acted as if they perceived it. How they perceive it (the information for the target affordance) remains to be explored.

The Affordances of Prehistoric Objects

Throwing, it turns out, is a human specialisation. While other animals have been known to throw things, none can match the speed, distance and accuracy of a trained human. Physical adaptations to support throwing have been evolving in the human lineage for 2 million years (Roach, Venkadesan, Rainbow & Lieberman, 2013) and the relationship between the size-weight illusion and the perception of throwing affordances suggests we have psychological adaptations as well (Zhu & Bingham, 2011).

One of the most common early technologies found at sites of prehistoric human activity is the spheroid, a rock shaped by either nature or hand to be fairly spherical. Their exact function is unknown. One hypothesis, however, is that they served as projectiles for hunting (e.g. Isaac, 1987; Mason, 1988). We recently tested this hypothesis using our affordance analyses, in collaboration with Lawrence Barham and Ian Stanistreet (Wilson, Zhu, Barham, Stanistreet & Bingham, 2016).

We examined a spherical subset of spheroids from the Cave of Hearths, a site in South Africa (Mason, 1988; McNabb & Sinclair, 2009). These objects are at most 500,000 years old, and were formed by natural weathering processes in a river about 2km from the cave. The evidence suggests that these objects were selected and transported by the humans living at the cave for some purpose. We know from the work above that modern humans can perceive the relatively optimal objects for throwing from a set that varies in size and weight such as might be found in a river bed (Bingham et al, 1989; Zhu & Bingham, 2008, 2010; Zhu, Dapena & Bingham, 2009; Zhu, Mirich & Bingham, 2014). If the spheroids were intended to be projectiles, they should all ideally afford throwing.

We first simulated the projectile motions these spheroids would undergo if thrown by a modern human, using parameters from the maximum distance work cited above (e.g. Zhu & Bingham, 2008; Zhu, Dapena & Bingham, 2009; throwing for maximum distance involves maximising release speed, which also then maximise impact forces). We found the objects could be thrown 20-40m and at release speeds of around $17ms^{-1}$. At various points in the trajectory, we then computed the damage each object would do to a medium sized prey animal (an impala). We used the Blunt Criterion (BC; Sturdivan, Viano & Champion, 2004) which is an energy ratio of the energy imparted by the impact divided by the target’s ability to absorb that energy. Sturdivan et al also regressed BC scores with measured injury damage and that equation enabled us to estimate the probability of a given amount of damage for each object.

We found that 81% of the spheroids tested were in the ideal range to optimise damage when thrown, and that if they hit the target they had a better than even chance of breaking a bone, even at maximum distance. No single spheroid could kill an impala, but given that humans hunted in groups even a few hits would have substantially slowed the animal down, making it much easier prey. The spheroids show every sign of having been selected to be thrown for impact by prehistoric humans.

Affordances as Perceived Task Goals

Finally in this chapter, we want to identify for the record a soon-to-be-tested relationship between our affordance analysis and movement variability analyses such as the uncontrolled manifold analysis (e.g. Scholz & Schöner, 1999).

As described above, the cardinal feature of the perception-action system is the degrees of freedom problem (Bernstein, 1967). Our bodies have more elements that can change their state than are typically ever required for any given movement. This means that there are an indefinite number of solutions to each and every task demand. This poses an extraordinarily complex control problem – out of all the movement trajectories we *can* make, how and why do we select and implement the ones that we *do* make? Theories of motor control must therefore provide solutions to both the problem of *action selection* and *action control.*

Traditional solutions to this problem replace the indefinitely large set of possible movement trajectories with a single 'desired' action trajectory, either by imposing a cost function (e.g. minimising jerk; Flash & Hogan, 1985) or by assembling a synergy in which multiple degrees of freedom can be controlled as a single device to produce a single outcome (e.g. Turvey, 1990). However, these solutions are a) underconstrained themselves (which cost function? Which synergy?

Why?) and b) do not fit the typical data, in which trajectory variability remains the rule and not the exception.

A more recent framing of the problem is the *motor abundance hypothesis* (Latash, 2008, 2012). From this perspective, there is no single optimal movement. Instead, because there are always many movement trajectories that can satisfy a task goal, the goal of motor control must be to preserve the outcome, not a specific implementation. In other words, the human action system must exhibit *degeneracy* (e.g. Whitacre & Bender, 2010).

All movements show variability, but not all variability is equal. Some will prevent you from achieving the goal state, some will not. In the motor abundance framework, the job of the action control system changes from selecting optimal trajectories to the strategic deployment of control. The system only applies active control if the current variability will cause failure to preserve the required outcome. This will sometimes entail changing trajectories part-way through movements, but this is a) possible because the system is not having a single trajectory imposed on it and b) still functional because of the degeneracy. The motor abundance hypothesis is that this arrangement enables an organism to continuously have access to movement options to preserve flexibility, while still simplifying the control problem to the point where it is solvable.

This approach is embodied in several formal data analysis techniques, which all focus on analysing the structure of the variability in movements relative to a task demand (a *performance variable*). These analyses include the uncontrolled manifold (UCM; e.g. Scholz & Schöner, 1999), stochastic optimal control theory (e.g. Todorov & Jordan, 2002), nonlinear covariation (e.g. Müller & Sternad, 2003) and the goal equivalent manifold (e.g. Cusumano & Cesari, 2006). These techniques all have different origins and motivations but all embody the key ideas of the motor abundance hypothesis, and generally converge on the same kind of solution to the problem of motor control, specifically online feedback control relative to a task goal.

All these analyses assume that the system is working to achieve a task goal, but none of them include a theory about what that goal is or how it is perceived. In fact, Todorov & Jordan (2002) explicitly identify that there as yet are no principled ways to independently identify how people perceive the task. The general solution is to simply set the goal to be the task instructions from the experimenter. From the first-person perspective of the organism, however, task goals must be create information and be perceived in order to be able to affect behaviour. We need a method for characterising the perception of action-relevant task goals in terms that would enable the goal-oriented deployment of control processes by an actual organism.

It should come as no surprise at this point that we believe our affordance methods to be exactly the methods required by the analyses. For example, the affordance maps identify the set of release parameters leading to a hit. This quantifies the affordance of the target to be hit by throwing, or, in other words, it quantifies the action relevant task goal/performance variable. We therefore hypothesise that the strategic deployment of control processes described by motor abundance analyses is driven by the real-time perception of task-dynamically defined affordances.

This relationship can be seen in the affordance maps from the targeted throwing paper (Wilson et al, 2016a). The set of release parameters (action variables) that lead to a hit is a multi-valued subset of the total parameter space; a manifold. Variation within this manifold does not need to be controlled away; the combinations all lead to hits. We saw clear signs that end point variability across trials was being organised with respect to this manifold, but we did not collect the necessary full body motion capture data required for, say, UCM analysis. We will be running this study shortly.

Another feature of our analysis is that the affordance manifolds vary in their stability. All values within the manifold led to hits, but not all regions of the manifold tolerated error to the same degree, and the most stable regions shifted around with, for example, changes in orientation (Wilson et al, 2016a). Building manifolds from the bottom up, based on real parts and processes, enables us to quantify the internal structure of the manifold itself in a way that does not yet really feature in the literature.

There is another intriguing hypothesis we believe we can test using these methods. Motor abundance analyses all assume that the system is primarily a feedback control system; in fact, Todorov & Jordan (2002) explicitly show that this is the optimal control architecture when possible, and detail the criteria for when it is possible. Online feedback control for a throw is not always possible at every moment in an action; for example, the movement may be too fast (although see data on extremely late corrections in Urbin, 2013) or the hand may not be in view. If control is only exerted when the relation between the limb and the task goal can be perceived, then changes in the various variability measures across a trial should index the onset and offset of perceptual control. We believe this strong interpretation would be licensed by the fact our manifolds are defined with respect to real parts and processes (affordances and the perception of affordances).

Uncontrolled manifold analysis can be performed at various stages of a movement (e.g. Yang & Scholz, 2005). Changes in the relative amounts of acceptable variability that leave you on the manifold (V_{UCM}) and problematic variability that takes you off it (V_{ORT}) can be tracked over time within a movement. If V_{ORT} begins to increase and is not immediately reduced by a control process, this suggests the real time, feedback control system is not currently active. When V_{ORT} begins to get removed, feedback control has come back online. For us, the feedback control system is using information about performance relative to the perceived task affordances. Therefore our second hypothesis is that changes in the way V_{UCM} and V_{ORT} shrink and grow over a movement indexes the onset and offset of affordance based feedback control (c.f. Fajen, 2005, 2007). This will provide information about what is being perceived, when and how (e.g. if control of the arm requires vision of the arm).

All of this remains to be explicitly tested, but there is clear conceptual overlap between the motor abundance hypothesis and the ecological approach to perception and action. If these hypotheses are supported, our affordance analysis will close a gap in motor abundance analyses and provide a way of formally defining both the task, the task goals and the resulting pattern of control used to achieve that goal all in the same dynamical framework and language. This upgraded *perception-action abundance* framework enables truly causal mechanistic *explanations* of the process of perception-action control (explanations grounded in reference to real parts and processes; Bechtel & Abrahamsen, 2010; Craver, 2007).

Conclusion

Functional behaviour is that which successfully complements the demands of the current task. Tasks can be formally characterised in terms of their dynamics, and each task offers opportunities for actions to different organisms – tasks have affordances. Affordances can be quantified by using the task dynamics in the context of specific actions and behaviours, and the research we have described here has had great success in explaining, rather than simply describing, why people do what they do in the presence of the different affordances that support various parts of throwing for distance and accuracy.

Throwing itself is a fascinating task for many reasons. It is a unique human specialisation, and there is growing evidence for the crucial role it has played in our evolutionary success by enabling our weak bipedal ape ancestors to hunt a variety of prey animals. The act itself is also a beautiful example of the exquisite timing and control the human perception-action system is capable of, and best of all the tools now exist to study it rigorously in the lab in its natural form. Modern motion capture technology, coupled to the new motor abundance style analyses shaped and guided by our task dynamical affordance framework will allow us to continue to make big strides in understanding and explaining the mechanisms underpinning throwing performance, and this research programme will stand as an exemplar to guide research on other actions.

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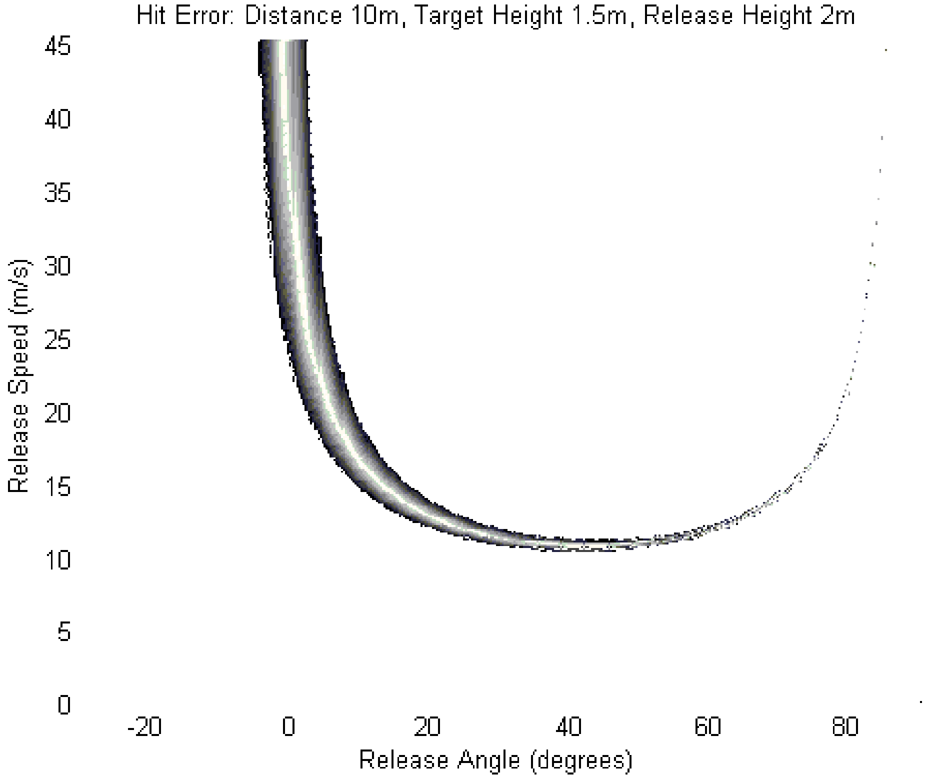
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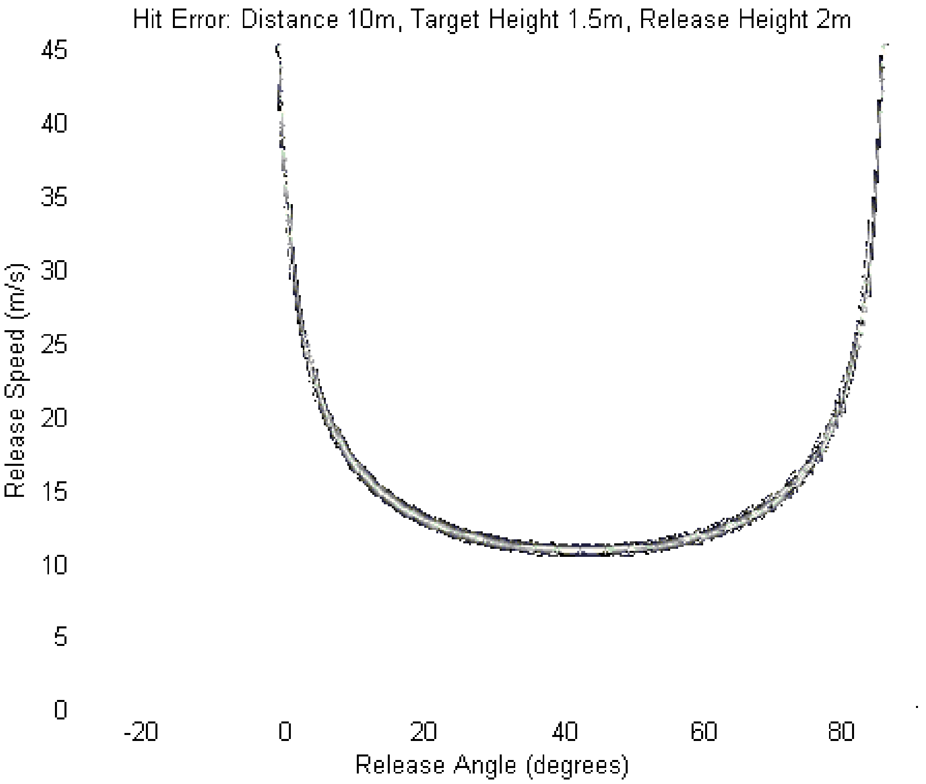
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Figure 1. Affordance maps for throwing to hit a vertical (top panel) and horizontal (bottom panel) target, both located 10m away and at a height of 1.5m. See text and Wilson, Weightman, Bingham & Zhu (2016) for more details.