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A Systematic Review of Perception of Affordances for the Person-Plus-Object System

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Abstract

Background Human behavior often involves the use of an object held by or attached to the body, which modifies the individual's action capabilities. Moreover, most everyday behaviors consist of sets of behaviors that are nested over multiple spatial and temporal scales, which require perceiving and acting on nested affordances for the person-plus-object system. This systematic review investigates how individuals attune to information about affordances involving the person-plus-object system and how they (re)calibrate their actions to relevant information.

Methods We analyzed 71 articles—34 on attunement and 37 on (re)calibration with healthy participants—that experimentally investigated the processes involved in the perception of affordances for the person-plus-object system (including attunement, calibration, and recalibration).

Results With respect to attunement, objects attached to the body create a multiplicity of affordances for the person-plus-object system, and individuals learned (1) to detect information about affordances of (and for) the person-plus-object system in a task and (2) to choose whether, when, and how to exploit those affordances to perform that task. Concerning (re)calibration, individuals were able (1) to quickly scale their actions in relation to the (changed) action capabilities of the person-plus-object system and (2) to perceive multiple functionally equivalent ways to exploit the affordances of that system, and these abilities improved with practice.

Conclusions Perceiving affordances for the person-plus-object system involves learning to detect the information about such affordances (attunement) and the scaling of behaviors to such information (calibration). These processes imply a general ability to incorporate an object attached to the body into an integrated person-plus-object system.

Keywords: ecological psychology, perception-action, attunement, calibration

Introduction

A fundamental concept of Gibson's ecological approach to perception-action is that of affordance (J. J. Gibson, 1979). Affordances are opportunities for action as higher order, emergent relations in the animal-environment system (Stoffregen, 2003a). That is, affordances emerge from the multifaceted relationship or fit between animal and environment. In any given situation, there are a multitude of affordances (i.e., a field of affordances; see Bruineberg & Rietveld, 2014). Which of the multitude of affordances are perceived as well as whether, when, and how any of these affordances are actualized depend on the intentions of the animal (Shaw & Kinsella-Shaw, 1988)—specifically the overarching goal(s) to be achieved and the behavior(s) required to do so.

However, behaviors are not performed in isolation. Achieving a given overarching goal typically requires that a particular set of behaviors be performed in a particular way given a particular set of circumstances. That is, behaviors are both nested within other behaviors (over multiple spatial and temporal scales) and within the goals for which and circumstances under which those behaviors occur. Consequently, affordances for a given behavior are nested within other affordances (over multiple spatial and temporal scales, Stoffregen, 2003b) and within the goals for which and the context within in which those affordances are perceived (Bingham & Muchisky, 1995).

Depending on the overarching goal to be achieved, the set of behaviors required to achieve that outcome can be performed sequentially, simultaneously or in parallel (i.e., simultaneously but independently of one another). Consequently, depending on the particular goal-directed behavior to be performed, the set of affordances for behaviors that yield the intended outcome can likewise be perceived sequentially, simultaneously or in parallel (Mark et al., 2015). Moreover, perceiving, or actualizing a given affordance can influence what affordances are subsequently perceived or actualized (Ye et al., 2009). This implies that a given affordance can be superordinate to (of higher-order than) or subordinate to (of lower-order than) another (Wagman et al., 2016a). That is, higher-order affordances may emerge from the relationship between lower-order affordances (Peker, Böge, Bailey, Wagman & Stoffregen, in press).

One way to conceptualize the relationship between higher- and lower-order affordances is as a means-ends hierarchy (Vicente & Rasmussen, 1990; Wagman et al., 2016a, but see discussion of a possible alternative heterarchical organization in the Discussion section). According to Vicente & Rasmussen (1990), each level of the hierarchy includes a set of affordances that relate to the *why*, *what* and *how* of performing a behavior. At any level of the hierarchy, affordances are simultaneously and mutually constrained by the other levels, rather than in a strict top-down fashion. In this conceptualization, the behavior itself (e.g., using a ladder) is performed at the (intermediate) '*what'* level. This level represents the specific behaviors to be performed but does not represent either the goals for which they are being performed or the means by which they could be performed. The superordinate (*why*) level relates to the goals of the behavior— why one engages in this behavior (e.g., retrieving an object)—but does not prescribe the specific behaviors necessary to achieve that goal. The subordinate (*how*) level, on the other hand, relates to means by which the behavior can be carried out (e.g., stepping). In addition, in this conceptualization, perceiving affordances for a given behavior does not correspond to perceiving affordances for a specific sequence of behaviors but rather to a field of possibilities that generalizes beyond any particular sequence (Wagman et al., 2019). That is, perceiving affordances for a given behavior simultaneously reflects affordances nested at both lower and higher levels of the hierarchy.

In many (if not all) cases, affordances emerge from a multifaceted fit between the animal's action capabilities and the substances, surfaces, places, objects, and events that comprise the animal's niche (see Richardson et al., 2008). Consequently, the same substances, surfaces, places, objects, and events may or may not afford the same behavior for two different animals (even of the same species) depending on the specific action capabilities of each animal (Fajen, 2008).

Action capabilities (and hence, perception of affordances) are determined, in part, by an animal's anthropometric properties. For example, Warren (1984), found that (perception of) the boundary between stairs that afford climbing and those that do not could be expressed as a body-scaled ratio of 0.88 between leg length and step height. However, action capabilities are also determined by more dynamic properties such as strength, coordination, and balance. Accordingly, experimental findings have shown that flexibility and leg strength also contribute to (perception of) affordances for stair climbing (Konczak et al., 1992). Consequently, perception of affordances is likely best captured through action-scaled (rather than body-scaled) metrics because (maximum) action capabilities and skills influence not only the ability to perform a given goal-directed behavior but also both attunement (i.e., pick-up of information) and calibration (i.e., scaling of action) of perception of affordances for that behavior (Fajen, 2005). In other words, body-scaled affordances are a special case of action-scaled affordances (Comalli et al., 2013; Day et al., 2015; Franchak & Adolph, 2014).

Attunement, or the education of attention (E. J. Gibson, 1969; J. J. Gibson, 1966), has been defined as the process of progressively detecting patterns in lawfully structured energy arrays that provide increasingly useful information about a given affordance. In other words, performing a given behavior for a given overarching goal under a particular set of circumstances requires that an animal detect information about a very particular multifaceted fit between animal and environment (Jacobs & Michaels, 2007). The more complex the goals for which a given behavior is being performed and the more complex the circumstances under which that behavior is being performed, the more specific the information about that fit becomes. Additionally, given that any given goal can be achieved by a variety of different behaviors, and any given behavior can be performed in a variety of different ways, a given goal-directed behavior can be performed in multiple ways and by multiple means. This means that performing a goal-directed behavior requires flexibly and temporarily recruiting potentially independent anatomical components into a smart—task-specific—device capable of achieving the goal-directed goal (Bingham, 1988; Runeson, 1977).

Consequently, successfully performing a given goal directed behavior requires that animals precisely scale choices about whether, when, and how to perform a given behavior to their action capabilities (Fajen, 2007). The process that establishes and maintains the scaling between action (and perception) and information about a given affordance to make such choices is known as calibration (Withagen & Michaels, 2005). Of course, perceiving and acting capabilities change over both the short term and long term. In many cases, such changes require recalibration—learning a new scaling relationship between information about affordances for a given behavior and whether, when, and how to perform that behavior (Brand & de Oliveira, 2017; Franchak & Adolph, 2014; Franchak, 2017).

In general, studies indicate that perception of affordances for a given behavior increasingly reflect an animal's action capabilities as they become attuned to (as they learn to detect) the information about a given affordance (Fajen & Devaney, 2006). Moreover, as animals learn to detect more useful information about a given affordance, they can learn (become calibrated to) how to use that information to more precisely scale choices about whether, when, and how to perform that behavior and they can relearn (recalibrate) how to do so when circumstances change (Fajen, 2005). For instance, experience in a given perception-action task typically leads a perceiver toward detecting and exploiting increasingly useful informational variables that enable increasingly fine-tuned perceiving and behaving (Jacobs et al., 2000, 2001; Jacobs & Michaels, 2002, 2007).

In this respect, it could be argued that over the course of long-term practice, experts in a given perception-action task (1) have learned to detect more useful information about task-specific affordances than novices (Araújo et al., 2005), (2) have become more precisely calibrated to how use such information to perform such tasks. It could also be argued that given more finely developed abilities to detect information about task-specific affordances coupled with more finely developed abilities to exploit such information about task-specific affordances, experts in a given perception-action task also have (3) more finely developed abilities to perceive task-specific action boundaries than do novices.

Given that experts have highly developed abilities to detect and exploit information about task-specific affordances, they are better able to use (1) many different coordination patterns to perform a given task-specific behavior over the short term and (2) many different behavioral patterns (i.e., many different nestings of coordination patterns) to achieve a given task-specific overarching goal over the long term. In other words, experts can re-organize multiple degrees of freedoms at multiple levels and over multiple time scales to achieve consistent performance outcomes (Seifert et al., 2016). In the biological systems literature, the ability of structurally different elements to yield same outcome is known as degeneracy (Edelman & Gally, 2001).

Degeneracy seems to be a fundamental property of biological systems at many different levels of organization and scale (Mason, 2015).

Recently, researchers have used the concept of degeneracy to better understand the stable yet flexible performance of skilled athletes. As an example, Seifert et al. (2021) found that expert climbers exhibited variable behavioral patterns both within and between bouts of climbing. In a climbing task involving nested affordances, participants were asked to touch or grasp a rock-climbing hold in a number of different ways: (1) by either moving their hand or the foot first; (2) by using either a face-on or side-on body position to the wall; and (3) by using multiple the support points. The results showed that the complexity of the nesting of affordances modified both the number of degrees of freedom available to the climber (i.e., number of joints or limbs involved in the coordination) and the likelihood of combining actions in a temporal sequence. These findings suggest that the nesting of affordances allows climbers to exploit degeneracy and open up new possibilities for climbing. One way to investigate the nesting of affordances is through the person-plus-object-system.

Tool-use

In everyday life, the objects used in the course of performing many goal-directed activities change the action capabilities of the animal and thereby alter the fit between animal and environment. An object attached to or held by an animal creates an integrated person-plus-object system with a unique sets of action capabilities and control dynamics. Such objects simultaneously increase action capabilities for some tasks (e.g., the ability to reach distant objects) and decrease them for other tasks (e.g., the ability to fit through narrow spaces). Therefore, animals must be able to perceive how an attached or held object changes the task-specific affordances for performing a given goal-directed behavior over the short term and for achieving multiple overarching goals over the long term. That is, perceiving affordances of and for the person-plus-object system should require the same processes of attunement, calibration and recalibration as are required for perceiving affordances for the person without such an object. To this end, it is important to consider person-plus-object system as a spontaneously assembled smart instrument (see Carello, Fitzpatrick, Domaniewicz, et al., 1992; Runeson, 1977). Doing so means that (1) a given person-plus-object system is temporarily assembled specifically for a given task, (2) the same person-plus-object system can be assembled over many different anatomical structures, and (3) many different person-plus-object systems can be assembled over the same anatomical structures.

A large body of research has explored the presumption that the information that supports perceptual capabilities with respect to the person-plus-object system is defined over the invariant patterns of deformation of the body's muscular and connective tissues that occur when manipulating the attached or held object. Therefore, perceiving affordances of and for the person-plus-object system should require the same processes of attunement and calibration to information in making choices about whether, when, and how to perform a given behavior with or with respect to the person-plus-object system.

Overall aims

Despite sustained interest in the topic of affordances and the ubiquity with which objects are held by or attached to an animal in the course of performing everyday behavior, an understanding of perception of affordances of and for the person-plus object system is still emerging (see Mangalam et al., 2022). Moreover, no systematic review of this topic was available at the time of our search. Based on this body of literature, this systematic review aims to establish the state of science regarding the perception of affordances of and for the person-plus-object system. The central research questions in this systematic review are related to how humans become attuned to the information about affordances of and for the person-plus-object system and calibrate their actions to such information. To answer this question, we discuss the scientific literature in two main categories. The first set of studies that we reviewed were those examining attunement: these studies investigated the detection of informational variables that support perception of affordances for the person-plus-object system, in particular, how such detection changes with practice. The second set of studies we reviewed were those examining calibration and recalibration: these studies focus on the degree to which perceived action boundaries on a given behavior reflect the actual action boundaries on that behavior, and in particular, how this relation changes with practice. Then we make suggestions for future research and how those processes could be understood as being organized heterarchically (as opposed to hierarchically).

Methods

Eligibility

Studies were included in the systematic review if (1) they included healthy human participants; (2) they investigated perception of affordances (implicitly or explicitly) of or for the person-plus-object system; (3) they used physical objects (rather than a virtual object or an image of an object); (4) they were experimental studies (if there was manipulation of an independent variable); (5) the study referred to attunement, calibration or recalibration; (6) were published in an English-language peer-reviewed journal as an original full-length paper (i.e., not a review or conference paper).

Search strategy

Literature search and selection were carried out according to the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) (Moher et al., 2009). The initial search was conducted in November 2021, with additional searched carried out in January 2023. A three-step procedure was used to identify relevant studies. First, we selected Pubmed, APA PsychArticle and Psychology and Behavioural Sciences Collection as relevant databases to identify studies that met the inclusion criteria summarized above. Each search was structured to include two sets of terms; the first set relating to the person-plus-object system: object, wear, tool-use, handheld, altered body, locomotion, dynamic touch; and the second set relating to ecological psychology: affordance, perception-action coupling, ecological approach, ecological psychology, body-scaled, action-scaled, attunement, calibration, recalibration. The terms included within each of these collections were separated with the operator ‘OR’, while the two collections of terms were linked with the operator ‘AND’. All possible variants of words like ‘change’ and ‘decrease’ were entered in databases. We included the title, abstract, keywords, and topic as search areas. To further identify relevant studies, we reviewed the reference lists and citation of all studies identified in step one. The titles and abstracts of all papers retrieved via the systematic search strategy were exclusively screened by the first author (PV) based on the outlined inclusion criteria. Next, the remaining full-text studies were screened using the same inclusion criteria.

Quality assessment

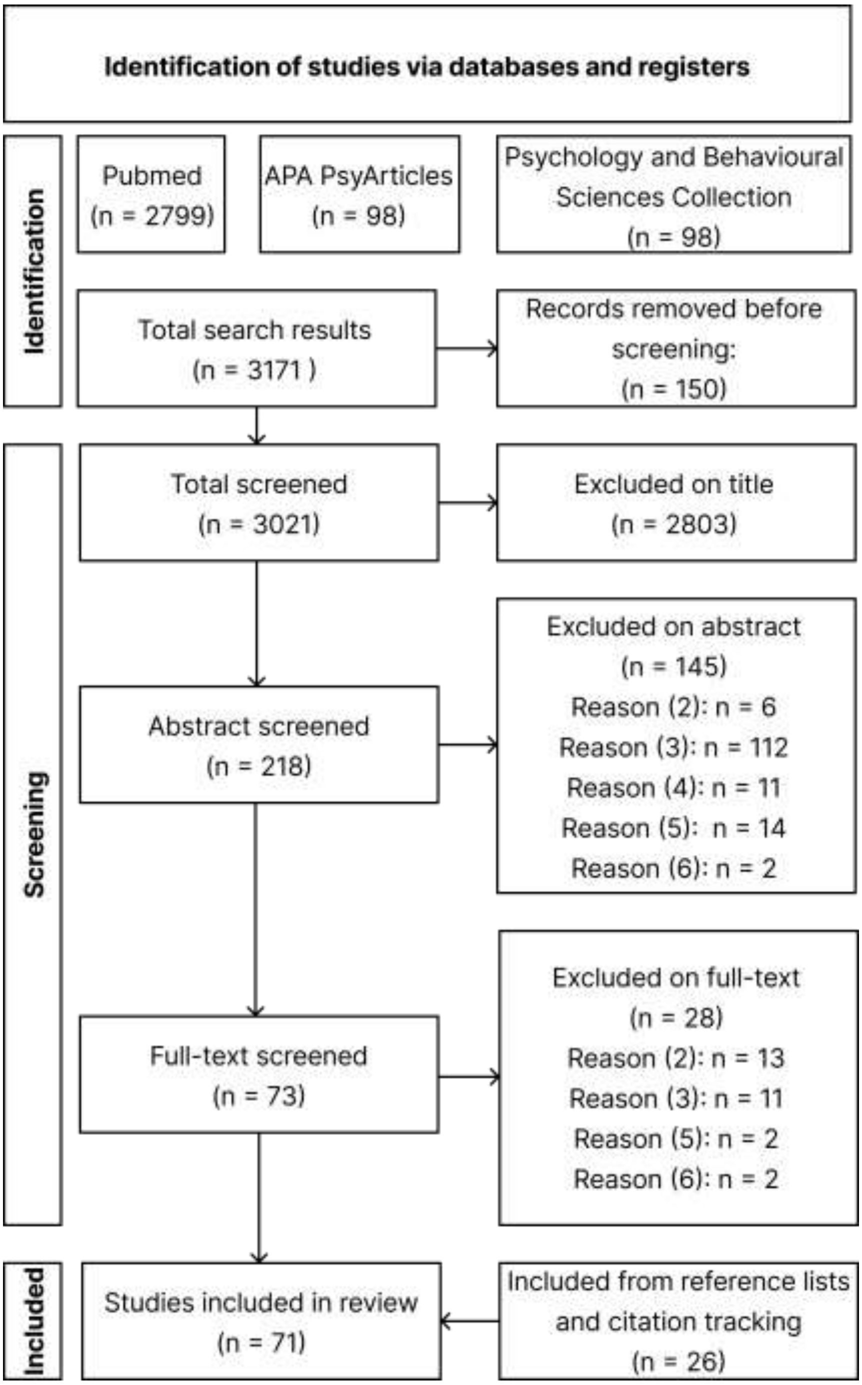
The quality of the studies was assessed using the *Crowe Critical Appraisal Tool* (CCAT) (Crowe, 2013) which was developed based on a wide number of previous critical appraisal tools, general research methods theory and reporting guidelines and exhibits high construct validity (Crowe et al., 2011) and reliability (Crowe et al., 2012). Quality assessment is a standard part of systematic review and informs on the methodological quality of the included articles (Hohn et al., 2019), notably the CCAT is composed of eight categories representing the various aspects of a study, including abstract, introduction, design, sampling, data collection, research ethics, results, and discussion. Each category contains a number of attributes, which are marked as present, absent, or not applicable and are scored on a scale from 0 to 5. The scores for the eight categories are then added together and summarized as a percentage to indicate the paper's overall methodological quality. As the CCAT protocol does not provide a specific protocol for interpreting the score, and as each category does not have the same weight, the range of possible scores for each category was divided in terciles, with articles assessed as exhibiting either; i) low (0-1); ii) moderate (2-3); or high (4-5) methodological quality; then a global score was generated as the sum of all the categories and was expressed as a percentage (for another example of systematic review using the CCAT, see van Andel et al., 2017). The results of the quality assessment are available as Online Resource (**Supplementary Materials, Table 1 and Figure 1)**.

Result

Study selection

The literature search in Pubmed, APA PsycArticles and Psychology and Behavioural Sciences Collection resulted in 3171 hits (2799, 98 and 279 hits respectively). We removed 150 duplicates resulting in 3021 unique references. Of these 3021 references, 73 met the inclusion criteria based on a reading of the titles and abstracts, and 45 of these met the criterion based on a reading of the full text. An additional 26 references were included based on a review of the reference lists and citations of these 45 references, yielding a total of 71 references that were included in this review. The literature search and selection process are displayed in Figure 1.

Figure 1. Flowchart summarizing the process of article selection. *Note:* Reasons for exclusion are listed in the subsection: Eligibility.



Descriptive statistics

Characteristics and results of the 71 studies included in this systematic review are summarized in Online Resource (**Supplementary Materials, Table 2**). Studies are published in 20 different journals; most were published in Ecological Psychology (22%), followed by Attention, Perception & Psychophysics (14%) and Experimental Brain Research (11%). Thirty-three articles

(46%) reported multi-experimental articles with two or more experiments, leading to a total of 136 experiments conducted.

Of all the studies, 48% (n = 34) investigated attunement. More specifically 13 investigated attunement to constraints related to the task itself, 10 investigated attunement to constraints related to the object itself, and 11 investigated attunement to constraints related to the individuals themselves. 52% (n = 37) investigated calibration or recalibration. More specifically, 16 investigated calibration to constraints related to the task constraints, 14 investigated calibration to constraints related to the object, and 7 investigated calibration to constraints related to the individuals themselves.

Attunement

Task

Perceiving affordances or other properties of the person-plus-objects system requires detecting the mechanical parameters that are invariant over transformation (e.g., as the object is being manipulated). This means that detecting such parameters is a process of actively differentiating those mechanical parameters that vary over such transformations and those that do not. This process is part of what leads to attunement to such invariant mechanical parameters with practice in a given perceptual task (especially when feedback is provided).

Michaels et al. (2007) asked a group of participants to rate how well eight different objects afforded performing twelve different tasks. They found that the patterns of ratings that emerged in participants who simultaneously looked at and wielded the objects were not different from the patterns that emerged when they only looked at *but did not* wield the objects. However, it is important to consider that participants who wielded the objects did not have the opportunity to explore its use, an experience that may have been sufficient to bring about a change in their ratings. Studies of perceptual learning have demonstrated that participants can shift from a less informative variable to a more informative variable after feedback. Wagman et al. (2001) asked participants to perceive the height or width of wielded objects before and after different kinds of practice. Results showed that participants became attuned to a more informative variable occurred only when feedback was included as part of practice. Similarly, Withagen and Michaels (2005) provided participants with visual feedback about rod length in their first experiment and with feedback about verbal feedback about whether two rods were of the same length or of different lengths in their second experiment. Such feedback induced a switch from a non-specifying variable in pre-test to a specifying variable in post-test for most of the participants. To further explored the role of information gathered by feedback on attunement, Menger and Withagen (2009) asked whether attunement can transfer between a wielding context and a holding context. Experiment 1 consisted of a testing phase in which participants estimated the length of a held (but not wielded) rod and a feedback phase in which participants reported the length of a wielded rod and were provided feedback about actual length of the rod. In Experiment 2, the mechanical contexts (holding or wielding) were reversed. Results suggest improvement in the holding context transferred to the wielding context, but not vice versa.

De Vries et al. (2015) investigated the transfer of attunement between anatomical components. Specifically, participants had to estimate the length of a rod with both hands and both feet, before and after receiving feedback about judgements made with one the effectors. Training the hand resulted in increased attunement for both hands but not with the feet. Conversely, training one of the feet lead to smaller improvement for all the anatomical parts. The authors suggest that the ability to control and explore an object with an effector could be an important factor to become increasingly attuned to a specifying variable.

Arzamarski et al. (2010) expanded these studies on perceptual learning to investigate how a change of intention might affect attunement. First, their results replicated previous studies by showing that when participants perceive either the height or the width of wielded objects and received feedback, they gradually shift toward detecting the specifying variable for that particular property. Second, they found that when participants change intention—from perceiving length to perceiving width, or vice versa—they show dramatic changes in which specifying variable they detect. Similar results were obtained by Wagman and Carello (2001, exp. 1) and Wagman et al. (2016a) showing that affordances for using an object in a hammering task and in a poking task were specified by different variables. The same is true for categorizing objects as being more appropriate for performing a hooking or sliding task on a target object (Wagman et al., 2016b).

Thomas and Riley (2015, exp. 1) confirmed that intention influenced which informational variables participants detected and used in both perceiving and remembering a given property of a wielded object. They asked participants to perform two tasks— (1) judge affordances for reaching with a pair of wielded rods, and then —after the rods were no longer present— (2) judge the (remembered) heaviness of each rod. Participants judged that the two rods were differently heavy only when they expected to perform both tasks (likely because they were able to attend to information about both properties during the first task). Conversely, participants judged that the two rods were equally heavy when they only expected to perform the first task (likely because they only attended to information about affordances for reaching with the rod and not the heaviness of that rod). In addition, Ye et al. (2009) presented objects that had multiple affordances to participants. Participants were asked to identify all objects that afforded a particular behavior, and then identify all objects that afforded a different behavior. The authors observed that perceiving a given object to afford a given behavior decreased the likelihood of perceiving the same object to afford other behaviors, presumably because of what informational variables were detected initially.

Wagman et al. (2016a) observed that when participants assemble tools for use in different tool use tasks, they create tools with larger principal moment of inertia values when those tools are to be used in a striking task than when they are to be used in a poking task. These results parallel Hove et al.’s (2006) findings that participants rate the suitability of differently weighted hockey sticks based on the behavior to be performed with that stick (generate the most force on a puck or accurately maneuver a puck). Follow up experiments found that, after performing each of these tasks, participants adjusted their ratings to reflect how well the objects could be used in each task.

Environment

A detached object is part of the surrounding environment and is external to the individual. However, when held or attached to the body, the object is no longer merely a part of the environment. It is a part of the person-plus-object system, and the individual must perceive the shift in the boundary between him or her and the environment such that the object is included as a part of this system (J. J. Gibson, 1979).

To this end, researchers have shown that affordances for the person-plus-object system are perceived as such and not as a combination of (properties or) affordances for the person and (properties or) affordances of the object. Both Thomas & Riley (2014) and Wagman & Stoffregen (2020) found that perception of affordances for reaching with a tool was not reducible to an additive combination of perception of affordances for reaching (without the tool) plus perceived tool length. Similarly, Thomas & Riley (2014) also found that perception of affordances for passing through an aperture while holding an object was not reducible to an additive combination of perception of affordances for passing through the aperture (without the object) and perceived object width. Thomas et al. (2017) went further by examining the effect of practice on this perception. They found that while perception of affordances for reaching with a tool improves over trials, perception of tool length does not. Moreover, in a follow up study, they found that only perception of affordances for reaching with a tool (and not perception of tool length) improved with practice and such improvements did not transfer to perception of tool length.

Individuals have to learn what objects are manipulable and how they can be manipulated. Steenbergen et al. (1997) found that young children alter their grip on different spoons so as to maintain a functional relationship between the spoon and rice that was being scooped and transferred to a bowl. Later research by Wagman and Carello (2003) showed that participants modulate their grasp position for hammering so as to create a person-plus-object system with inertial properties appropriate for the specific task. Thus, participants chose a grasp position on a tool that maximized the volume of the inertial ellipsoid (*V*) in order to hammer with power; and that preserved *V* and the symmetry of the inertial ellipsoid (*S*) while minimizing the eigenvectors (e_k; i.e., the symmetry axes of the hand-object system) in order to hammer with precision. In the same way, participants choose a striking location on given both the grasp location on that object and the specific striking task (Wagman & Taylor, 2004). Mangalam et al. (2019) showed that the discovery of tooling affordances can be facilitated by emphasizing a change in inertial properties. Indeed, participants made fewer configuration changes and took fewer trials to render a heavier object (consisting of a blade and a shaft) a functional hoe than they did with a lighter object.

Along similar lines, individuals need to learn how to manipulate the person-plus-object system when performing behaviors such as passing through an aperture. Higuchi et al. (2009) found that under such circumstances, the gaze patterns used to detect information about affordances for crossing depended on the extent to which the object changed the behavior of the participant. These results suggest that when perceiving affordances for crossing an aperture for the person-plus-object system, the exploratory behaviors used to detect information differ only when the object fundamentally changes the action capabilities (and subsequent behavior) of the participant. Fixation patterns remained unchanged while walking, while walking while holding a horizontal bar without shoulder rotation, and walking while holding a horizontal bar with shoulder rotations. However, fixation patterns moved toward door edge throughout locomotion more frequently when crossing the aperture in a wheelchair.

By changing the location of the attachment of an object to the body, Malek & Wagman (2008) and Regia-Corte & Wagman (2008) showed that perception of affordances for standing on an inclined surface varied depending on whether and how a weighted backpack was worn. Specifically, perception of affordances was influenced by whether the backpack was worn on the front, the back, or not at all (Malek & Wagman, 2008) as well as the height at which the backpack was worn on the back (Regia-Corte & Wagman, 2008).

Individual

Individual characteristics (e.g., aging, expertise, body composition) have an important role in the perception of affordances in general and thus may also influence attunement in the person-plus-object system. The studies included in this review have investigated how attunement occurs over development, but also how it differs between different members of a given population.

Several studies have investigated how such abilities develop by asking children to perceive and use objects attached to or held by the body in various tasks. van Leeuwen et al. (1994) asked children to retrieve a target object using a hooked stick that was placed in different configurations, creating different spatial and temporal complexity in the behavior. The first experiment identified three distinct groups of participants. The first group comprised the oldest children who showed a high success rate for the three simplest configurations but a slightly lower success rate for the two hardest configurations. A second group comprised the youngest children who were mostly unsuccessful for all configurations. A third group was composed of children of different ages whose success rate decreased as task complexity increased. In the second experiment, the participants performed the task in order of decreasing complexity—from hardest to easiest. The results showed that once a child performed the task successfully, they subsequently performed the task successfully on all remaining trials. Finally, in the third experiment van Leeuwen et al (1994) included the possibility of performing the task with the straight portion of the hooked stick. Two groups emerged, one group that successfully used the hooked stick using both sections of the stick (curved and straight sections) and another group that only used only one section of the stick (either curved or straight sections). Interestingly, the group that could use the hook in both ways (curved and straight sections) showed a higher rate of success.

Keen et al. (2014) also observed better coordination of the person-plus-spoon system in older children (8-years-olds) compared to younger children (4-year-olds) in feeding task. The researchers asked children to use a spoon to feed themselves, a puppet on their lap, or a puppet facing away from them. The 4-year-olds showed high inter- and intra-individual variability in how they performed this task, including using less effective grips. In comparison, the group of 8-year-olds mostly used more effective grips that varied according to task. Fragaszy et al. (2016) investigated how 1- to 2-year-old children explored and used hammers depending on the presence or absence of a handle and the hardness of the surface to be struck with the hammer. They observed that children's ability to use the hammer improved from 1- to 2-year-old, both in terms of precision and kinematic force employed. Fitzpatrick et al. (2012, 2018) directly compared the performance of preschool aged children (3-5) years old to adults in a task that required hammerings pegs into a pegboard. Both the preschool aged children and the adults were able to discriminate and modulate some aspect of the hammering task in response to variation in the inertial properties of the hammers. However, the performance of the preschool children was still not as good as that of the adults in this respect. Specifically, children were less consistent in their grasping, hammered fewer pegs and produced smaller amplitude movements than the adults.

Aging is related to a variety of changes in the perception-action systems, and we might expect that age would bring about changes in the ability to perceive affordances. Carello et al. (2000) found both young (approximatively 19 years of age) and older adults (starting from 62 years of age) could perceive affordances for reaching with and the location of the sweet spot of a tennis racket. However, the older adults perceived the sweet spot as being closer to the hand, especially for long rackets. Those results were replicated by Chang et al. (2008), who also found that experience in playing a racket sport—rather than age alone—was a stronger factor in explaining the difference observed.

To further examine whether attunement deteriorates with aging, Withagen and Caljouw (2011) trained young and elderly to perceive affordances for reaching with a rod (i.e., participants received visual information about the length after they made the report). They found that young adults successfully learned to detect a specifying variable, while the elderly continued to rely on non-specifying variable. They concluded that the ability to attune to specifying variables declines with aging.

In addition, studies have explored whether there are individual differences in perception of affordances across members of a given population. Both Withagen and van Wermeskerken (2009) and Rop and Withagen (2014) have found differences in the way individuals respond to feedback about perception of affordances for reaching with a rod. Withagen and van Wermeskerken (2009) found that individuals varied in whether, when and how they respond to feedback over the course of seven test blocks and six feedback blocks. Three learning profiles stood out: (1) those who detected the specifying information in at least one test phase; (2) those who relied on non-specifying variables during all phases and appeared not to benefit from feedback; and (3) those who were affected by the feedback but still relied on non-specifying variables. Rop and Withagen (2014) explored whether such individual differences are due to variability in the ability to detect non-specifying variables, which may lead to continued reliance on such variables. One group received feedback on perceived length for a set of rods in which there was a low correlation between actual length and non-specifying variables (such as static moment); the other group received feedback for a set of rods in which there was a stronger correlation between actual length and non-specifying variables. Participants were less likely to benefit from feedback and exhibited more variability when there was a stronger correlation between non-specifying variables and actual length. This suggests that individuals vary in their ability to use feedback to shift from detecting non-specifying to detecting specifying variables.

Finally, Muroi and Higuchi (2017) investigated perception of affordances for passing through an aperture while holding an object horizontally under different vision conditions—a static vision condition in which participants viewed the aperture at the start of the trial but had to pass through it with vision occluded, a full vision condition in which vision was never occluded, and two dynamic vision conditions in which participants were required to stop and start again after taking two steps and then pass through the aperture with or without vision occluded. They found that perception of affordances in this task depended on whether the task was performed continuously (i.e., without stopping) and whether (and when) vision was occluded while performing the task. In particular, in all conditions in which vision was occluded, participants failed to make appropriate body rotations resulting in frequent collisions.

Calibration

Task

An object attached or held to the body changes the person's action capabilities, but these changes will have different consequences depending on the particular task to be performed or the constraints of that task. Studies have investigated both calibration of perception to such changes in a particular task and transfer of such calibration to a different task.

Withagen and Michaels (2007) examined whether recalibration in dynamic touch transfers between functionally equivalent tasks. In their first experiment, they examined if calibration of perception of affordances for reaching (i.e., length) transferred to perception of the location of the sweet-spot, and in their second experiment, they examined whether calibration transferred in the other direction. They found that calibration transferred from perception of affordances for reaching (i.e., length) to perception of the location of the sweet-spot, but calibration transferred in the other direction only in half of the participants. Along the same lines, Wagman & Van Norman (2011) showed that when (visual) feedback was provided, calibration transferred (1) between different grasps positions (i.e., middle and end) for a given task, (2) between different tasks (i.e., perceiving whole and partial length) and (3) between different grasps positions and different tasks. Similarly, Franchak (2020) examined whether calibration could transfer between perception of affordances for squeezing and fitting through narrow doorways while wearing a backpack. He showed that perception of affordances improved only in the practiced task and that no transfer was observed between squeezing and fitting, or vice versa. Petrucci et al. (2016) compared perception of affordances for passing over, under, or between obstacles by firefighters wearing protective equipment. The results showed both underestimation and overestimation of action boundaries both of which may create important safety concerns during a rescue. It was pointed out by Petrucci and colleagues that variability among equipment across fire departments may be a contributing factor to the results.

Abney et al. (2014) compared different types of feedback (experimenter feedback vs. changing the grasp position on the object) to investigate the improvement of perception of affordances for reaching with an object. Results showed that ratio between perceived and actual reachable distance improved for both type of practices, approaching 1.0. Practice have also been observed to improve perception of affordances for squeezing through a narrow space by participants wearing a pregnancy pack (Franchak & Adolph, 2014, exp. 3), reducing the error judgment from 10.5 cm to 2.4 cm.

Franchak (2017) asked five groups to report their ability to fit through doorways before and after different practice experiences. In each practice experience, participants had different sources of information available to them – optic flow, vision of backpack, haptic feedback. In addition, some practiced by performing the action of fitting through the doorway and some did not. The results showed that only the groups that practiced the action or received feedback about judgement accuracy showed recalibration in the posttest. Ishak et al. (2019) obtained comparable results in perception of affordances for crawling under a barrier while wearing a backpack. Participants were asked to choose the largest backpack (ranging from 10 – 30 cm thick) that they could wear and safely low crawl under a barrier. They performed the task before and after choosing the backpack (Pre/Post experience), only after choosing the backpack (feedback experience) or without choosing a backpack (no experience). The results showed that the Pre/Post experience group exhibited lower failure rates, probably because they were more conservative in choosing a backpack width compared to other groups. In a related task in which participants were asked to squeeze through a narrow space with a backpack, Franchak & Somoano (2018) showed that recalibration occurs quickly—rather than gradually—after participants receive outcome feedback, resulting in errors being reduced by 2-3 cm. In a second experiment, they investigated how the success/failure outcome feedback (practice or verbal) sequence (failure first, success first or interleaved order) affects perceptual learning. Calibration occurred when all participants received both successful and failed outcome feedback, regardless of sequence order or the type of feedback.

However, in some cases, limited practice is not sufficient to recalibrate perception of affordances for all tasks involving the person-object system. Yasuda et al. (2014) asked three practice groups (high-resolution, low-resolution and control) to report their ability to pass through apertures while holding an horizontal bar (exp. 1) or while using a wheelchair (exp. 2). They found that perception of this affordance was improved for both practice groups (HR and LR) while holding the bar but not when using a wheelchair. Likewise, in Higuchi et al. (2004) three groups of participants reported perceived affordances for passing through an aperture in a wheelchair. The authors found that even 8 days of practice was insufficient to completely calibrate perception of affordances for this behavior, although some improvements did occur.

Many of the studies included in this review investigated whether certain kinds of exploratory movements are necessary or sufficient for calibration or recalibration of perception of affordances for the person-plus-object system. In some of these studies, participants reported whether or not they would be able to pass under a barrier while in a wheelchair (Yu et al., 2010; Yu & Stoffregen, 2012). Participants were less calibrated to their ability to perform this task when head and torso movements were restrained prior to and during the sessions. However, Yu & Stoffregen (2012) found that accuracy of judgements was unaffected when the head was restrained if the participants did not have active control over their locomotion during the practice session. Likewise, Higuchi et al. (2006) found that when participants passed through an aperture while holding an object or while using a wheelchair, constraints on shoulder rotation were critical to the rate of calibration. In another study, participants were asked to report whether they could pass under a barrier while using a wheelchair (Stoffregen et al., 2009). One group received 2 minutes of wheelchair locomotion practice, another received 2 minutes of task practice, and the last group received no practice. Perceived minimum barrier height better reflected actual minimum barrier height in the practice groups; however, no group improved across trials. Participants who practiced using the wheelchair— and especially those that practiced the specific task— showed lower variability in head and torso velocity and path length. In two other studies, participants estimated the maximum height at which they could sit when they were wearing 10 cm blocks on their feet (that increased the maximum height of a surface on which they could sit) (Mark et al., 1990; Stoffregen et al., 2005). In the study by Mark et al. (1990), participants were able to recalibrate to their changed sitting ability only when their exploratory body sway movements were relatively unconstrained. Stoffregen et al. (2005) confirmed that changes in exploratory body sway were related to calibration of perception of affordances for sitting. Specifically, participants who recalibrated exhibited a decrease in the variability of head and torso movement.

Environment

As described earlier, an object attached to or held by the body changes a person's action capabilities. Research has examined both the individual's ability to perceive the new maximal action capabilities and their ability to act near this maximum for a given task.

Mark (1987) found that when participants wore 10-cm blocks on the soles of their shoes, perception of maximum sitting height improved over the course of twelve trials (that did not include practice sitting), approaching the same ratio of perceived-to-maximum as when no blocks were attached. However, perception of block height did not improve. Similarly, Hirose & Nishio (2001) found improvement in perception of affordances for sitting and stepping while wearing geta shoes (but only when surface heights were presented in an ascending order), a pattern that also occurred when not wearing the shoes. A number of studies extended these results to other tasks. Wagman & Taylor (2005) found that participants were able to perceive affordances for carrying an object through a doorway regardless of whether they were able to see the rod. Wagman & Malek (2007) showed that perception of this affordance is also influenced by the anticipated speed of locomotion through the aperture while carrying an object. Although this perception is not related to the individual's action capabilities, they showed that the perceptual boundaries (in relation to the object width) decreases when the participant anticipates running rather than walking. Ramenzoni et al. (2008) showed that participants could perceive affordances for reaching-while-jumping both for themselves and for another person and could perceive how such affordances changed when they or the other person were wearing ankle weights. Ishak (2008, exp. 3) asked participants to reach through an aperture using their dominant hand with and without a prosthesis that increased hand width. They found that participants adjusted their reaching behavior based on how the prosthesis changed their hand size. Franchak & Adolph (2014, exp. 2) compared perception of affordances for squeezing though a narrow doorway with and without wearing a pregnancy pack. Although the group who wore pregnancy pack were less accurate than the group who did not, they still made accurate judgments in relation to the change in their body dimensions. Comalli et al. (2017) investigated whether wearing ankle weights affected whether participants choose to step over or duck under a horizontal barrier. Results showed that participants exhibited the same transition point between these two behaviors (stepping over and ducking) when ankle weights were worn and when they were not.

In several studies included in this review, participants reported their maximum vertical reaching height when they expected to reach by various means (such as while standing on the floor, while standing on a stool and, with a hand-held tool). Wagman & Morgan (2010) found that participants were sensitive to how each means of reaching would increase maximum reaching height and when the two means would do so equivalently. Wagman et al. (2013) found that this occurred both when the two objects were visible and after they were removed from view. That is, perception of maximum reaching height was scaled to reaching ability equivalently for (1) both means of reaching and (2) when the tool was visible or out of view.

Wagman et al. (2019) found that participants are better calibrated to perception of affordances for reaching with the arm than with a hand-held object. The ratio of perceived to maximum action capabilities was less than 1.0 in both cases but was closer to 1.0 for touching than for grasping and for reaching with hand than with the tool. In other studies, using a pre-test, practice, post-test design, participants were asked to report their maximum reaching height if they were to reach while standing on their heels, on their toes, with or without a tool (Wagman, 2012, exp. 2) or kneeling, standing and using a step (Wagman et al., 2014). One group practiced the task by making the estimation and then performing the action. Another group only estimated their maximum reach height, without performing the action. The results showed that perceived maximum reaching height more closely reflected actual maximum reaching height for all means of reaching (different positions, with and without an object) following practice but only when practice included reaching attempts.

Withagen and Michaels (2004) and Stephen and Hajnal (2011) investigated transfer of calibration between anatomical components. Specifically, participants reported the perceived length of a rod wielded with the left hand and right hand (Withagen & Michaels, 2004) or with hand and with the foot (Stephen & Hajnal, 2011) before and after receiving feedback about perceptual reports in one of these conditions. Ratios between perceived length and actual length showed an improvement in the post-test regardless of the effectors trained so long as the participant had received feedback.

Individual

Given perception of affordances scales to (differences in) action capabilities, studies have investigated whether perception of affordances for the person-plus-object system similarly scales to (differences in) action capabilities.

Pepping & Li (2000) asked women and men to report their maximal overhead reaching ability with and without wearing 15-cm blocks on their feet. As expected, the perception of affordance in each condition was scaled to action capabilities and was not dependent of the sex of the person. Similarly, Wagman & Smith (2018) found that the maximum step-with-crutches distance was scaled to the participant’s leg length and reflected their actual ability to perform this behavior.

Perception of affordances for the person-plus-object system has also been studied across different age groups. Franchak (2019) compared the ability of young children, older children and adults to recalibrate perception of affordances for squeezing through a narrow doorway while wearing a backpack. He found that participants who generated feedback through (succeeding or failing while) attempting the task made more accurate judgments than those who did not. Overall, in this study, adults had lower absolute error than older children, who themselves had smaller absolute error than young children. Finkel et al. (2019) investigated recalibration of perception of affordances for reaching through an opening by both young and older adults who wore a splint on their hand for 24-hours. They were tested before, immediately after, 24-hours after wearing the splint and then directly after removing the splint. Young adults were able to recalibrate perception of affordances, but they were more conservative when perceiving affordances for reaching with than without the splint. Older adults exhibited a perceptual boundary at a smaller opening before wearing the splint and while wearing the splint than young adults. After the 24-hours period of wearing the splint, both groups tended to show recalibration of perception of affordances.

Another method to examine the effect of (longer-term) practice on perception of affordances for the person-plus-object system is through expertise. Higuchi et al. (2011) compared the ability of American football players, rugby players and control athletes to run or walk through an aperture, with or without wearing shoulder pads. The main result showed that American football players exhibited smaller magnitudes and later onset of shoulder rotation than rugby and control athletes, but only in conditions specific to the sport (i.e., running through aperture with shoulder pads). Moreover, every group tended to underestimate the absolute width of the shoulder pads. Also, in Pfaff and Cinelli (2018) rugby players crossed an aperture composed of either two poles or a pole and a person, while running or walking, with or without a ball. The result showed that participants displayed more restricted movement paths (e.g., reduced mediolateral movement of the center of mass) with the ball than without, and created more space between themselves and the aperture boundary when the aperture boundary included a person.

Finally, as for attunement, Hackney et al. (2014) found that participants recalibrated at different rates to changes in affordances for passing through an aperture while carrying a tray. Some recalibrated quickly and maintained their initial critical point (i.e., the minimum aperture width they could successfully cross) while others recalibrated gradually as the block of trials progressed and decreased the critical point.

Discussion

Main findings

Attunement

The results of this systematic review highlighted for attunement that: (1) individuals learn to detect information about a particular affordance for the person-plus-object system; (2) objects that are (or might be) attached to the body create a multiplicity of affordances for the person-plus-object system, requiring that the person choose which affordances to exploit and how to exploit them and; (3) perception of affordances for the person-plus-object system reflects how affordances are nested within the context of a particular task.

Information pick-up. Recent work suggests that objects attached to or held by the body become experienced as part of the body; therefore, the attunement should be with respect to information about affordances for the person-plus-object system. The results of our review are in line with this claim: studies showed that individuals perceive nested affordances for the person-plus-object system by detecting, attuning to, and calibrating action to information about such affordances.

Given that the information about a given affordance is invariant over transformation, individuals are able to detect information about a given affordance in different energy arrays by means of different perceptual systems. In addition, studies have shown that individuals exploit information about performing task-specific behaviors. In short, the information about affordances for the person-plus-object system seems to be dependent on a particular task but independent of a particular energy array.

By definition, affordances of any kind are emergent (or higher-order) relations within the animal-environment system (Stoffregen, 2003a). These higher order relations differ from the animal or environment components that comprise them. The same ought to be true for affordances for the person-plus-object system—that is, the higher order affordances for the person-plus-object system ought to differ from those for the person or of the object. In general, the results of the studies included this review suggest that this is the case. Accordingly, the studies included in this review suggest that the individual does not perceive the isolated properties that make up the system, such as the length of their arms or of the object itself, but rather he or she perceives the affordances for the person-plus-object system as such. Along similar lines, studies have shown that improvement in the perception of affordances for the person-plus-object-system is independent from improvements in perception of the properties that compose it.

Multiplicity of affordances. Generally, many different objects can be used to achieve the same goal and the same object can be used to achieve many different goals. The multiplicity of affordances gives rise to the questions of both intention (because perception of opportunities for action is goal-directed and involves choices) and object design (because objects will always have multiple affordances even if they are designed for a specific purpose). It has been shown that intention guides the detection of relevant informational variables that support perception of affordances. And, of course, the affordances of manufactured objects are constrained by the design of those objects. Thus, objects always afford multiple behaviors, and the individual must choose from among these to achieve the intended goal. On one hand, designing objects to afford a limited set of particular behaviors would facilitate the detection and exploitation of information about this particular set of affordances of that object, but doing so may make more difficult to detect and exploit information about other affordances. On the other hand, designing objects that afford many different behaviors would allow facilitate the detection and exploitation of information about many different affordances but may make it more difficult to (quickly) detect and exploit information about a particular affordance. Therefore, objects with a complex design could offer multiple affordances which would entail that sets of behaviors nested over spatial and temporal scales are specific to the goal-directed task. Future studies should take this property into account.

Relation between affordances*.* One fruitful framework for understanding relationships among affordances in performing a goal-directed task under a particular set of circumstances, is that of a means-ends hierarchy (Vicente & Rasmussen, 1990; see Wagman et al., 2016a). The results of the studies included in this review are consistent with sensitivity to the nesting relations among affordances in such a hierarchy (but should be considered subordinate to a broader analysis in terms of heterarchies, see Future research directions). Individuals were able to modify or create objects so as to perform a given behavior in the context of both the overarching goal and the underlying circumstances. For example, assembling a tool for use in a given task required participants to perceive affordances for the assembled tool both before and while it was being assembled. That is, participants had to create higher-order affordances for the person-plus-object system by exploiting lower order affordances (Wagman et al., 2016b). Consequently, performing any goal-directed behavior entails perceiving (and thus detecting information about) affordances for nested behaviors. However, attunement to information about a given (nested) affordance is often insufficient for successful performance of a goal-directed behavior. In addition, individuals must also calibrate their actions to that information.

Calibration

The results of this systematic review highlighted that: (1) exploration is associated with (and often necessary for) improved calibration and or recalibration; (2) individuals quickly recalibrate to changes brought on by an object attached to or held by the body; (3) calibration to a given affordance for the person-plus-object system can bring about functionally equivalent changes in perception of other affordances for the person-plus-object system.

Exploration for calibration. Exploration (i.e., moving so as to facilitate detection of invariant patterns in ambient energy arrays) generates information about the animal-environment system, including the person-plus-object system. According to the studies included in this review, the degree of calibration is related to the ability of the individual to explore ambient energy arrays via movements, even movements as subtle as postural sway. The more constraints on exploratory movement, the less the individuals were able to calibrate to changed action capabilities. Although generation and pick-up of information can occur during actions that are not explicitly exploratory (see Hacques et al., 2021), exploration to achieve the goal facilitates calibration improvement and/or recalibration.

Action boundaries. To perform a goal-directed behavior successfully and safely, individuals must be sensitive to the boundaries of their action capabilities for performing that behavior (Fajen, 2007). Objects attached to or held by the body modify the action capabilities and require recalibration to the new action boundaries. Broadly, studies show that individuals are sensitive to how an object attached to the body changes their action capabilities (and thus changes affordances for) a particular task. However, this may depend on the specifics of both the object and of the task (Higuchi et al., 2004; Yasuda et al., 2014) and future studies should expand this area of research.

In terms of the relation between perceived action capabilities, individuals were able to maintain the same ratio (between perceived:maximum and actual:maximum) for affordances for the person-plus-object system as for the person (without the object), highlighting the ability to quickly recalibrate after a period of practice. Results included in this review indicated recalibration to new action capabilities was facilitated with task-relevant experience and developmental changes in action capabilities, especially into early adulthood. However, recalibration to changed action capabilities is sometimes less well facilitated, either because of more conservative choices or because of declines in action capabilities. Overall, task-specific experience and expertise seems to lead to a better calibration or recalibration, but it remains unclear whether this is due to a decrease in the variability of behaviors that the individuals can perform, to a better awareness of action boundaries, to greater maximal action capabilities, or to some combination of these.

Functional equivalence. As highlighted previously, an object can be used to achieve several different goals, but a given goal can also be achieved by several different means or by means of using several different objects (i.e., relating to functional equivalence). Experiments have shown that two different (by functionally equivalent) means of reaching can bring about functional equivalent changes in perception of affordances for reaching for the person-plus-object system. In addition, in some circumstances, calibration of perception of affordances for performing a given behavior by one particular means transfers to perception of affordances for performing that behavior by a different means.

However, even though two objects may be used to achieve functionally equivalent ends, this does not necessarily mean that using those objects requires equivalent degrees of effort or ability. How individuals make decisions among those means is not well understood, particularly when functional equivalence could be observed and reflect skilled behavior Thus, skilled behavior could result in a multiplicity of possible action modes through the ability to accurately select an object to perform the behavior and the ability to incorporate the object to the animal-environment coupling. However, there is a lack of research investigating how skilled performers better incorporate the object into a person-plus-object system than less skilled performers, and then better perceive the multiply nested affordances and exhibit functional equivalence.

Future research directions

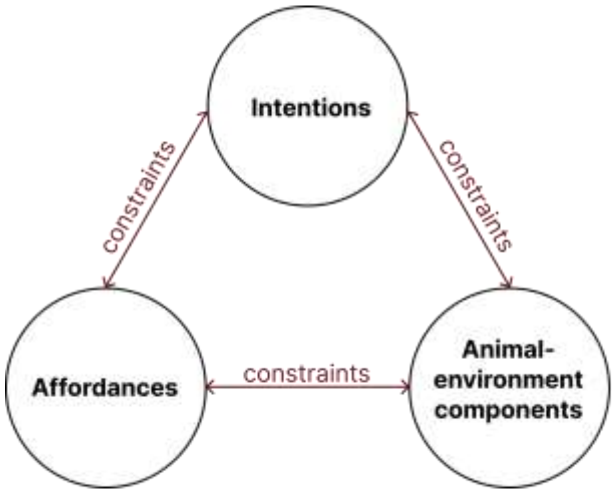
By reviewing the research on attunement and (re)calibration processes with respect to the person-plus-object system, our findings emphasized how the perception of affordances of an object attached to or held by the body facilitates the performance of functional equivalent behaviors in achieving the task goal. However, everyday behaviors are often considerably more complex (as several degrees of freedom must be coordinated to act synergistically) than simple lab-based activities, and it is unclear whether the results of such studies would be transferable to more complex situations. Thus, there is a lack of research investigating complex richly nested behaviors, particularly in relation to the unique control dynamics of the person-plus-object system and the many degrees of freedom involved in performing complex tasks.

In addition, investigating how the particular design of an object would offer multiple (nested) affordances depending on the skill of the individual would be of great interest to better design objects (Pagano et al., 2021) and to develop skill acquisition programs. Obviously, the ability of an individual to perform successful behaviors will vary depending on their action capabilities and how the object changes these action capabilities. This is an important focus for future research, especially for professions that require expertise such as athletes, firefighters, or military. It can be hypothesized that as the object becomes more complex, it may offer a wider range of affordances some of which may be less obvious to the individual. Furthermore, design complexity generally allows functional equivalence in tool use and raises the question of the selection of relevant affordance among the different possible action modes (Mangalam et al., 2019). For instance, expert climbers could exhibit functional equivalence in the movement pattern used to anchor their ice tool by using either swinging, kicking or hooking actions (Seifert et al., 2014). Although an individual can master some of these modes of action, it is coordination of these modes in the context of a given task that is the hallmark of expertise in that task—such as in skilled rock climbing.

We have considered the relationship between affordances of and for a person-plus-object system. In particular, we have done so in the context of the means-ends hierarchy developed by Vicente & Rasmussen (1990). However, hierarchies describe a choice that was made, not the process of choosing between the coexistence of many behavioral potentials in the perception-action system (see Profeta et al., 2020). To account for the multifaceted fit between individual and object that yields multiple affordances for the person-plus-object system, and more broadly how individuals organize their behavior effectively in their environment, we introduce the concept of heterarchy, which may be more consistent with a thoroughgoing ecological approach of perceiving and acting with the person-plus-object system (Shaw & Turvey, 1981). Unlike a hierarchy, a heterarchy has no fixed levels of elements, no fixed roles for elements, and no fixed relationship among elements. Instead, different sets of elements flexibly and dynamically emerge as particular circumstances unfold. Therefore, any given element in the system can have any number of ways to any number of other elements, depending on circumstance (Profeta et al., 2020).

In this view, intentions, affordances, and the animal-environment are components of an organizational system that are unranked with respect to one another or have the potential to be ranked in multiple ways with respect to one another (Figure 2). Consequently, the constraints are multidirectional and distributed across the many interacting components of the organizational system and subsystems. There are an unlimited number of intentions that an individual might have in any given situation, but a subset of these can be acted on at any given moment. For behavior to be successful, intentions must be related to the individual and the environment that surrounds him or her. In the situation where the environment does not meet the intentions, it can motivate exploration of the individual-environment system to achieve the intended goal (Stoffregen, 2003a). Similarly, an unlimited number of affordances emerge from the relationship between the animal and the environment, but only a subset of these actually stand out as relevant to the individual's current goals (i.e., the field of affordances) (Wagman et al, 2016b; Wagman, et al., 2019). For instance, the many affordances that comprise the heterarchy have the potential to be nested (over temporal and spatial scales) in different ways. This logical continuity is conveyed by Reed (1982): *"What makes an action what it is, is not the hierarchical integration of responses into some movement pattern, but rather, it is the nesting of control processes that organize postures and movements to serve some function".*

Figure 2. Goal-directed behavior heterarchy.

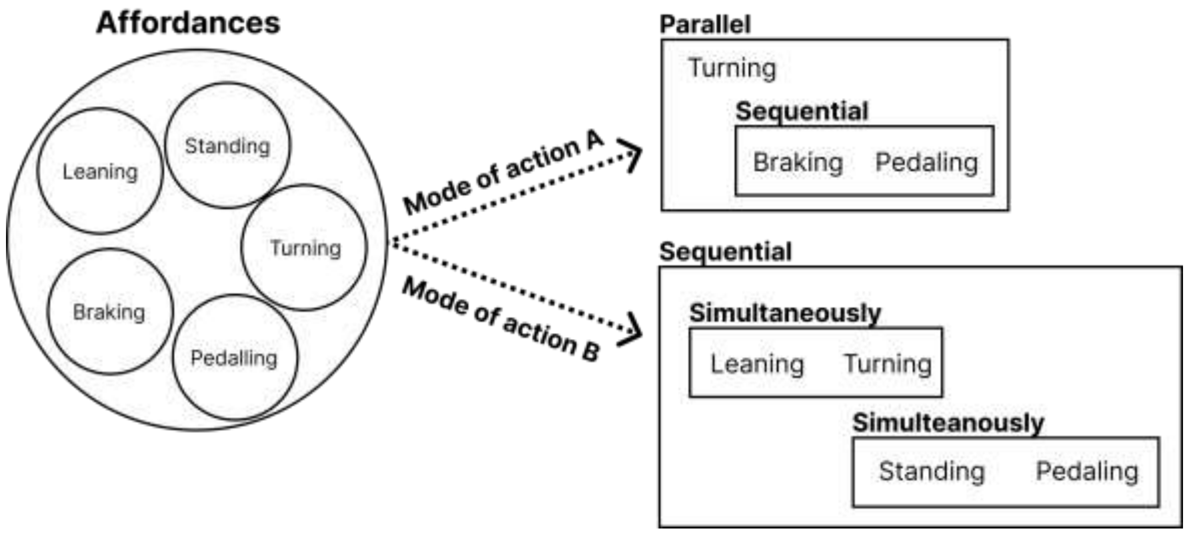


Inevitably, hierarchies emerge from heterarchies due to constraints of other systems and of the subsystems (Figure 3). Therefore, existing analyses of affordance nestings within means-ends hierarchies (Vicente & Rasmussen, 1990; Wagman et al., 2016) can be understood as being compatible with but subordinate to a broader analysis in terms of heterarchies (Profeta et al., 2020).

Following this view, the components of the animal and environment system are coordinated (i.e., functionally ordered in space and time)—resulting in synergies—to reduce the dimensionality of the system (i.e., complexity). Thus, in the case of a person-plus-object system, coordination patterns are assembled and disassembled by reordering the subsystems or components involved, as well as by recruiting or releasing them (Kelso et al., 1993).

The emergent skilled behavior is not merely a matter of appropriately switching from one action to another but also in appropriately coordinating the various means and various ends to generate and control multiple (and multiply nested) modes of action to perform the goal-directed behavior. For example, in the case of crossing an aperture while cycling, many actions are possible (leaning, standing, braking, etc.) and one of the possibilities to cross an aperture in cycling would be to adapt the speed based on the distance from the aperture, then turn the handlebars and lean the bike to successfully cross the aperture. In another situation, the individual could express a different mode of action such as braking from a certain distance of the obstacle to reduce his/her speed so that he/she can rotate the handlebar more accurately. Thus, hierarchies can emerge as situation-specific actualization of potentials due to constraints imposed upon the heterarchical logic (Profeta et al., 2020).

Figure 3. In the case of aperture crossing in bike, many affordances are available (e.g., leaning, standing, turning …) and the skilled behavior that will emerge is a coordination of the different elements to form a mode of action (in a means-ends hierarchy manner) in relation to the intentions and the individual-environment system.



This reconceptualization builds on the pioneering work by Shaw and Turvey (1981), Reed (1982) and Vicente and Rasmussen (1990) highlighting the coexistence of many potentials for behaving in perception-action systems, including person-plus-object system. Moreover, this reconceptualization emphasizes the degeneracy property of expert perception-action system by showing (1) how several means could be coordinated to achieve a given outcome, (i.e., exhibiting degeneracy: MANY structures - to - ONE function relationship; Edelman & Gally, 2001), but also (2) how those means and modes of action could achieve many different outcomes, i.e., exhibiting pluri-potentiality (Mason, 2010) or multi-functionality (Kelso, 2012) (ONE structure - to - MANY functions relationship). In Figure 3, degeneracy is exploited when several modes of action (i.e., pedaling, braking, leaning, turning) are nested differently to achieve the same goal (i.e., crossing the aperture). Likewise, pluri-potentiality is exploited when the same modes of action (i.e., pedaling, leaning, turning the handlebar) are coordinated to achieve different goals (i.e., crossing the aperture and 'dancing on the pedals' to climb a slope).

Conclusion

Overall, we conclude that individuals can perceive affordances of an object attached to or held by the body through the processes of attunement and calibration, implying a general ability to form a person-plus-object system. This systematic review revealed that the literature investigating perceiving and acting on affordances for the person-plus-object system is currently limited to nested affordances of relatively limited complexity. In particular, future research should investigate the use of objects with multiple degrees of freedom (objects with multiple affordances), how individuals coordinate the degrees of freedom of the object with the degrees of freedom of their body to achieve the overarching goal (if, when, how, they develop a synergy), and how individuals perceive different affordances of a given object in relation to achieving an overarching goal. Research lines worth pursuing when studying the affordance in the person-plus-object should include the study of task and object complexity and skill expertise.

Open practices statement. This systematic review does contain supplementary material and, this systematic review was not preregistered.

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