A Process Framework of Affordances in Design

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Introduction

One of the many goals of design research is to better understand the ways in which end users interact with the products of designing. This focus is not surprising—the ultimate measure of success for any design is the adoption by the user. The concept of affordance recently has been the focus of increased interest in the design research community because it captures well the relationship between human users and designed artifacts. It has been imported from cognitive science, where it was first introduced by the perceptual psychologist, James Gibson (1977, 1979):

> 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. (Gibson 1979, p. 127; emphasis is the author's)

Affordances in design are the action possibilities of a user when the user interacts with an artifact. They can be "directly" perceived, based on the structural features of the artifact. This understanding has the advantage that users do not need to be provided with explicit instructions about how to use the artifact. As a result, they can spend less cognitive effort and make fewer errors when interacting with the artifact.

Affordances are dynamic in that they emerge from the interaction between the user and the artifact. Users interact differently with the same artifact at different times (Vyas et al. 2006), which gives rise to different interpretations of affordances by these users. On the other hand, affordances tend to be generalized so that they are described no longer as specific to any individual user, but to groups of users or all users. This is apparent in the frequent use of word constructions ending with "-ability" when describing affordances. For example, the stairs in Figure 1 afford "climb-ability." Conceptualizing affordances as "-abilities" has the benefit that they can be thought of as general properties of artifacts that can be designed for or against. This conceptualization has established the basis for many affordance-based approaches to designing (Norman 2002; Galvao and Sato 2005; Maier and Fadel 2009a; Maier and Fadel 2009b).

Figure 1. Stairs affording "climb-ability"

Affordances can be viewed in two ways. One view describes affordances as *post-hoc* properties of a user-artifact system, and they are either known in advance or discovered by the user. Here, an affordance is assumed to pre-exist, regardless of whether the individual user is aware of that affordance. The alternative view emphasizes the situation of the user interacting with and reasoning about the artifact. In this view, affordances are defined with respect to the user's individual situation, rather than from the perspective of an omniscient observer. It allows new action possibilities to be generated as a response to changes in the user's experience or goals. This view closely matches Norman's (2002) notion of "perceived affordance," which we believe is more useful for design research than a *post-hoc* approach. However, to date there has been no clear articulation of perceived affordances or of the ways in which they can be produced.

This paper presents a process framework for perceived affordances to address this gap. (In the rest of this paper, we use the term "affordances" as shorthand for the notion of "perceived affordances.") It proposes three types of affordances that entail different assumptions regarding their dependence on the user's situation. All three types are then represented in the ontological situated function-behavior-structure framework (Gero and Kannengiesser 2004), revealing a rich set of processes involved in generating them. We argue that this view provides a better understanding of affordances that can be used for developing more methodological and tool support for designers.

An Ontological View of Affordances at a Macro Level

Modeling affordances is facilitated by using an ontological framework that provides a common terminology with agreed-on meanings for a domain of discourse. The function-behavior-structure (FBS) ontology (Gero 1990; Gero and Kannengiesser 2004) provides such a framework for the design domain.

Structure (S) of an artifact is defined as its components and their relationships (i.e., what the artifact consists of). The structure of artifacts includes their form (i.e., geometry and topology) and physical or virtual material.

Behavior (B) of an artifact is defined as the attributes that can be derived from its structure (i.e., what the artifact does). An example of behavior is the weight of an object, which can be derived (or measured) from the object's material and spatial dimensions, using knowledge about gravity and the material's density. Behavior provides operational, measurable performance criteria for comparing different artifacts. Deriving behavior may require knowledge about exogenous effects (i.e., the properties of those parts of the external environment that interact with the artifact). For example, deriving the rotational behavior of a door requires considering external, physical forces applied to that door. Exogenous effects can be caused by any entity in the artifact's environment, including human users.

Function (F) of an artifact is defined as its teleology (i.e., what the artifact is for). It is ascribed to behavior by establishing a teleological connection between a human's goals and measurable effects of the artifact. Function is independent of the common distinction between "functional" and "non-functional" properties; it comprises both as they describe the artifact's usefulness for various stakeholders. Function is also independent of specific modeling approaches, including flow-based (dynamic) and state-based (static) models (Chittaro and Kumar 1998).

In previous work, Brown and Blessing (2005) have argued that affordances appear to be similar to function but do not include the notion of teleology. Affordances also appear similar to behavior; however, it is not the behavior of the artifact but of the agent that can be driven by affordances. So how do affordances relate to our understanding of designed artifacts?

Affordances are an agent's potential actions that interact with an artifact's structure and thereby produce artifact behaviors of relevance (i.e., with positive or negative consequences). These actions can be captured in the FBS ontology as exogenous effects on behavior. Figure 2 consists of two shapes that symbolize affordances and behavior, respectively. For an affordance to interact with behavior, there needs to be a "fit" between the two. This fit can be illustrated by conceptualizing behavior as including an "input port," or "receptor," that metaphorically mirrors the shape of the affordance. In other words, we can define input parameters of behavior that represent the properties of the affordances to which the output of that behaviour is responsive.

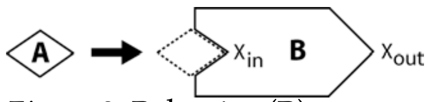

Figure 2. Behavior (B) as a construct that provides input parameters (X_{in}), representing relevant properties of affordances (A), and output parameters (X_{out}), representing the measurable states produced

This model of affordances as exogenous effects is consistent with Maier and Fadel's (2009a) view of affordances as connecting structure and behavior. However, affordances are not static catalysts for deriving behavior from structure in a reproducible, deterministic way. Human users engage with artifacts in a variety of ways as a result of their individual interpretation of the artifact's function, behavior, and structure; thus, they are unlike most computational tools that are preprogrammed to always derive the same class of behavior when given a specific class of structure. Our current macro-level view cannot show this dynamic model of affordances explicitly; we need to elaborate on this view to develop a more complete understanding of affordances.

Locating Affordances in a Framework of Reasoning

We can characterize affordances based on a framework for different general modes of reasoning of situated design agents that has been presented by Maher and Gero (2002). This framework provides a descriptive model rather than a cognitive model, and it has been used for elaborating various aspects of situatedness in design. The framework distinguishes between reflexive, reactive, and reflective modes of reasoning:

- *Reflexive reasoning* is a direct response of the agent to specific sets of stimuli to which it is exposed. Reasoning here does not entail any internal processing or decision making; it is merely a mapping of sensory input to actions performed by the agent's effectors. Examples include "hard-wired," biological reflexes and habituated responses to recurring stimuli. We can ascribe a high degree of confidence to reflexive reasoning that the resulting actions will produce the desired outcomes. This confidence is implicit in the actions rather than in an explicit, cognitive state of the agent.
- *Reactive reasoning* involves a limited form of interaction between various of the agent's internal representations. This interaction can be viewed as the process of selecting from several alternatives the most appropriate schema, given the stimuli presented. The need for decision making leads to a lower degree of confidence associated with the outcomes of the agent's actions. As a result, agents assess their decisions by monitoring the effects of their actions and comparing them against a set of criteria.
- *Reflective reasoning* involves a more significant amount of interaction between a model of the external world and the agent's goals and concepts. It is a construction process that uses filtering, emphasizing and distorting certain aspects of the external cues, driven by changes in the agent's expectations. The outcomes of actions devised by this mode of reasoning produce new expectations that provide new criteria for assessing these actions.

In computational experiments, Gero and Peng (2009) have shown that reflectively produced responses are grounded as new experiences that move toward being reactive as they are used in subsequent interactions, and reactively produced responses similarly move toward being reflexive as they are successfully used in subsequent interactions.

Based on the three modes of reasoning, we can derive three classes of affordances: reflexive, reactive, and reflective ones.

Reflexive Affordances

The notion of affordance as originally proposed by Gibson is a "direct" form of perception that is often interpreted as involving a very limited amount of internal processing. This description is consistent with the reflexive mode of reasoning, and consequently we call these affordances reflexive. All stimuli provided by the artifact are directly mapped onto the user's actions. The fit between artifact and user is via the user's sensorimotor system. This fit is most evident for affordances of physical objects that mirror the shapes of the human body, such as shoes and gloves. The sensory data (here, the form of the artifact) directly fits with the user's effectors (here, the human's feet and hands). The affordance of "wear-ability" in these cases can be labeled "intuitive" (Blackler et al. 2006).

Most affordances rely less on a strictly physical fit between artifact and user and instead involve more abstract classes of "fit" that require some internal representations (e.g., patterns and schemas) that match the external stimuli presented to the user. This type of connection is consistent with Norman's emphasis on the role of users' existing internal models in their perception of affordances (Norman 2002). For example, if a user has previously been exposed to a number of door handles with similar shapes, sizes, positions, and orientations, they will have constructed a schema that represents this class of artifact. When the user later comes across a particular door handle that matches this schema, the user can reflexively perform a set of actions associated with the schema, such as turning, pulling, pushing, or sliding the handle. The affordances of "turn-ability," "pull-ability," "push-ability," and "slideability” (Koutamanis 2006) can be seen as outcomes of reflexive reasoning processes that are precursors of these actions. Their parameters have default values (i.e., all actions are executed uniformly). Using the idea of parameterized behavior introduced in Figure 2, Figure 3 shows, how a reflexive affordance can be modeled as an input parameter with a fixed value.

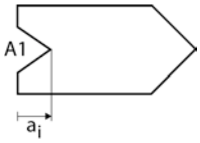

Figure 3. Reflexive affordance modeled within behavior as an input parameter A1 with a fixed (default) value a_i

Reactive Affordances
A reactive affordance is an action possibility that is selected from among a set of action possibilities. The process of selection is independent of changes in the user’s current goals and expected classes of concepts. Variations over time are often the result of the user acquiring new knowledge from previous interactions.

Reactive affordances can be seen as the outcomes of a search process, analogous to the notion of search in routine or parametric designing. The basis for searching affordances is the availability of a range of instances of a class of action possibilities, and the ability to assess and then select different instances using a set of criteria. Instances of a class of action possibilities differ in the values these action possibilities assign to parameters of that class.

Searching affordances can be carried out internally using thought experiments, or externally using physical experiments. Every experiment consists of generating an action possibility and then testing it according to a set of criteria. If it is found to be unsatisfactory, the user can iteratively select and test different action possibilities. For example, someone wanting to unlock a previously unknown door may turn the key the wrong way (say, clockwise). Upon recognizing the initial failure to unlock the door, the user selects an alternative action possibility (e.g., turning the key counter-clockwise), tests it, and finds that it successfully unlocks the door. The expectation that the key is to be turned has not changed during this process—only a parameter of this action (the direction of turning) has changed its values (from clockwise to counter-clockwise). Other examples of parametrically varying the same action possibility include turning the key with different forces, different speeds, and different fingers. Figure 4 shows how a reactive affordance can be modeled within behavior as an input parameter with varying values.

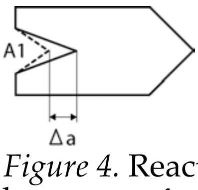

Figure 4. Reactive affordance modeled within behavior as an input parameter A1 with a range of values Δa

Reflective Affordances
Reflective affordances involve changes in the user’s expectations generated by different situations. Situations are processes that influence what goals and concepts are constructed and how agents interpret and interact with their environment (Gero and Smith 2009). For example, users of office doors are likely to respect the privacy of the people behind these doors; as a result, the new affordance of “knock-ability” may be formed, making the users knock on the door before entering. Other situations

(e.g., the imminent threat of an armed hold-up) may produce the new goal of blocking a door rather than walking through it and the new affordance of "jam-ability" (e.g., by jamming a chair underneath the door handle). Thus, different situations lead to different user expectations that can then produce different affordances. "Hidden affordances" (i.e., ones for which obvious perceptual cues are not provided by the artefact (Gaver 1991)) can be viewed as instances of reflective affordances.

The notion of exploration in non-routine or conceptual designing can be applied to describe how users "discover" new affordances via reflective reasoning. Exploration creates new expectations related to classes of action possibilities and their criteria for assessment. It is non-routine because the user can no longer rely solely on an existing set of expectations. Exploration can be modeled as modifying the state space of action possibilities.

Exploration can be carried out internally using thought experiments, or externally using physical experiments. The latter has been studied in developmental psychology and has been found to involve "exploratory activities" (Gibson 1988). For example, infants explore their environment through seeing, reaching, grasping, and tasting, among other actions. Discovering new door-opening mechanisms (e.g., button-operated automatic doors) requires a more fine-tuned but still exploratory set of actions. The exploratory nature of reflective affordances can enable a user to recognize "false affordances" (Gaver 1991) or "misinformation" (Gibson 1979) provided by the artifact.

Figure 5 shows how a reflective affordance can be modeled within behavior as a new type of input parameter.

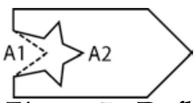

Figure 5. Reflective affordance modeled within behavior as a new type of input parameter A2, here substituting the previous type A1

An Ontological View of Affordances at a Micro Level

We can develop an ontological framework of affordances that goes beyond the narrow view of affordances as catalysts for deriving fixed and known behaviors. This view captures reflexive affordances but not reactive or reflective ones. However, the situated FBS framework developed by Gero and Kannengiesser (2004) can be used to capture all three classes of affordances.

The Situated FBS Framework

This section provides a brief description of the situated FBS framework; for more information, see Gero and Kannengiesser (2004).

Figure 6 introduces two "worlds": an *interpreted world* that represents current ("as-is"), past ("as-was"), and hypothetical ("as-could-be") states of the world, and an *expected world* that represents desired ("to-be") states of the world for the current design interaction. The different states of the world(s) are described using the concepts of function, behavior, and structure of the design representations. In the interpreted world, behavior (B^i) is derived from a given or hypothetical structure (S^i), and function (F^i) is derived from a given or hypothetical behavior (B^i). In the expected world, expectations are produced about what behaviors (Be^i) are needed to achieve desired functions (Fe^i), and what structures (Se^i) are needed to exhibit desired behaviors (Be^i). The expected world is a subset of the interpreted world, as indicated by their nesting in Figure 6. Accordingly, Fe^i, Be^i, and Se^i are defined as subsets of F^i, B^i, and S^i, respectively.

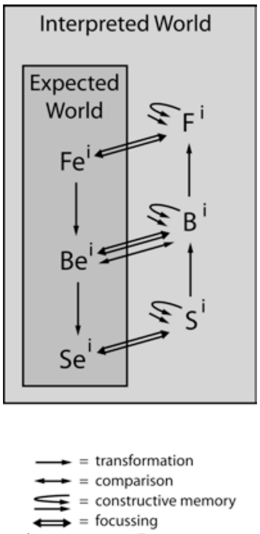

Figure 6. Function, behavior, and structure in the interpreted world (F^i: interpreted function, B^i: interpreted behavior, S^i: interpreted structure) and the expected world (Fe^i: expected function, Be^i: expected behavior, Se^i: expected structure)

In addition to the transformations between function, behavior, and structure within the two worlds, Figure 6 shows a number of additional processes:

- *Focusing* selects subsets of F^i, B^i, and S^i to be used as Fe^i, Be^i, and Se^i. Once selected, a subset is not fixed but can be changed by focusing on different F^i, B^i, or S^i.
- *Comparison* determines whether an "as-is" state of the world is consistent with a "to-be" state of the world. This process compares Be^i and B^i, as it is the behavior level that provides measurable attributes for evaluating different artifacts.
- *Constructive memory* can produce new F^i, B^i, and S^i. This process represents a richer notion of memory than simple recall via indexing. It includes the role of subjective, individual experience in constructing new concepts that are tailored to the agent's current situation (Dewey 1896; Bartlett 1932; Rosenfield 1988; Clancey 1997). Constructive memory can be modeled using the idea of intertwined data-push and expectation-pull (Gero and Fujii 2000), which is denoted in Figure 6 using a combined straight-and-returning arrow symbol.

Figure 7 is an extension of Figure 6. It adds the *external world*, which consists of things outside the agent, including the functions, behaviors, and structures (F^e, B^e, and S^e) of artifacts that the agent can interact with. The external world also includes requirements on the functions, behaviors, and structures (FR^e, BR^e, and SR^e) of artifacts. The process numbers in Figure 7 are labels only and do not represent an order of execution.

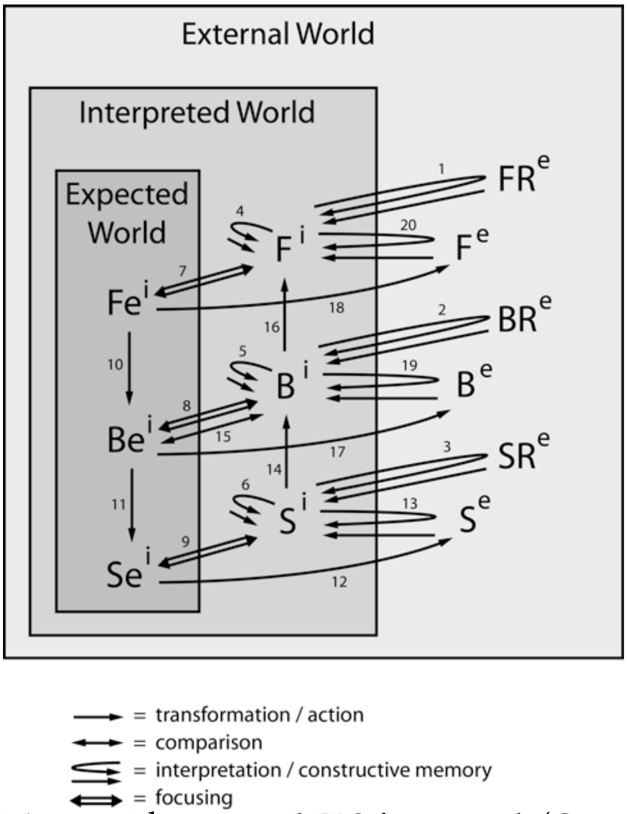

Figure 7. The situated FBS framework (Gero and Kannengiesser 2004) that includes function, behavior, and structure in the external world (F^e: external function, B^e: external behavior, S^e: external structure, FR^e: external requirements on function, BR^e: external requirements on behavior, SR^e: external requirements on structure)

Adding the external world introduces the processes that connect it with the expected world and the interpreted world:

- *Action* produces F^e, B^e, and S^e according to Fe^i, Be^i, and Se^i. Action producing B^e is the execution of expected design actions.
- *Interpretation* uses F^e, B^e, and S^e to produce F^i, B^i, and S^i using the same "push-pull" idea as for constructive memory: The results of interpretation are not simply "pushed" by what exists in the external world; instead, they emerge from the interaction of "push" and "pull." Thus, the same F^e, B^e, and S^e can be interpreted differently at different times, leading to changes in the F^i, B^i, and S^i generated.

Locating Affordances in the Situated FBS Framework

The situated FBS framework is general enough to capture the activities of a user interacting with an artifact because the notions of interpreted and expected worlds are independent of any specific agent and can relate to the designer, the user, or any other stakeholder. However, describing users' interactions with the artifact requires two specializing assumptions:

1. External structure and external behavior are embodied in the target environment of the design—not in a representation of that target environment. For example, the target environment of a door is the physical environment; possible representation environments include CAD systems, paper, and human minds.
2. Actions to create or change external behavior (process 17 in Figure 7) consist of those that produce exogenous effects that are also embodied in the target environment. Thus a user's actions are distinguished from those

of a designer, in that the latter are primarily concerned with changing representations of behavior rather than with the behavior itself. Affordances are the input parameters of behavior, as we explained earlier.

Affordances transform external structure into external behavior. This transformation involves at least the following sub-processes in Figure 7:

- Process 13: transforms S^e into S^i
- Process 14: transforms S^i into B^i
- Process 15: evaluates B^i against Be^i
- Process 17: transforms Be^i into B^e

These sub-processes compose what we call the *affordance production process*. Additional sub-processes for pre- and post-processing are required, depending on whether the affordances are reflexive, reactive, or reflective. The differences are summarized in Table 1 and discussed in more detail in the remainder of this section.

Table 1. Reflexive, reactive, and reflective affordances have the same production process but differ in their pre- and post-processing. Numbers refer to the processes defined in Figure 7.

<table>
<tr><th>Type</th><th>Pre-Processing</th><th>Affordance Production Process</th><th>Post-Processing</th></tr>
<tr><td>Reflexive</td><td>No pre-processing required</td><td rowspan="3">• Input: S^e
• Transform-ation:
13, 14, 15, 17
• Output: B^e</td><td>No post-processing required</td></tr>
<tr><td>Reactive</td><td>Any of:
• Selecting Be^i: 8
• Selecting Fe^i: 7</td><td>• Assessing the affordance: 19, 15
• Optionally, re-selecting Be^i and/or Fe^i by new pre-processing</td></tr>
<tr><td>Reflective</td><td>Any of:
• Constructing Be^i: 5, 8, 10
• Constructing Fe^i: 4, 7, 16</td><td>• Assessing the affordance: 19, 15
• Optionally, re-constructing Be^i and/or Fe^i by new pre-processing</td></tr>
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Reflexive Affordances
The processes involved in producing reflexive affordances are highlighted in Figure 8.

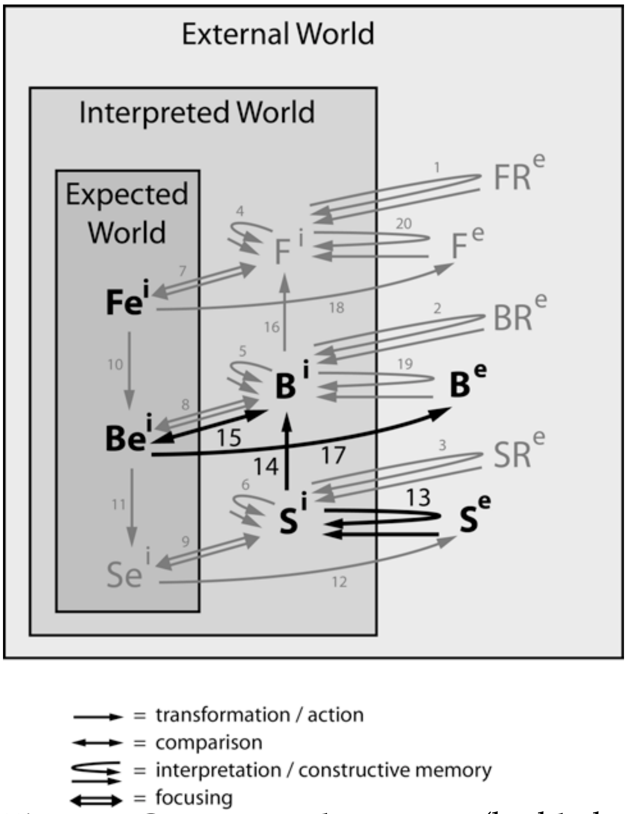

Figure 8. Concepts and processes (highlighted) in reflexive affordances

There is no pre-processing for reflexive affordances. Be^i and Fe^i are pre-formulated and readily provide a pattern to be matched by the interpretation of the artifact based on its S^e. All input parameters of Be^i have fixed values. For example, S^e may be a door with specific features, Fe^i may be "to allow access to a room," and Be^i may be a rotating behavior with fixed values for the direction (say e.g., "outward") and the amount of force one needs to apply to the (handle of the) door. Another example is a flight of stairs, as in Figure 1. Here, S^e consists of the shape of the stairs, Fe^i may be "to allow descent in a controlled way," and Be^i may be a "walking support" behavior with fixed values for the input parameters "stepping rhythm" and "speed."

The affordance production process establishes a match between the expectations and interpretations of the door and stairs, and then executes the affordance. No post-process monitoring or analysis of the external behavior is needed because the validation of the affordance is assumed by default. In the door example, a person pushes against the door to produce an external behavior using the expected values of direction and amount of force. In the stairs example, a person walks down the stairs to produce a walking support behavior with the expected values for stepping rhythm and speed. No post-process monitoring or analysis of the external behavior is needed, as the validation of the affordance is assumed by default.

Reactive Affordances

The processes involved in producing reactive affordances are highlighted in Figure 9.

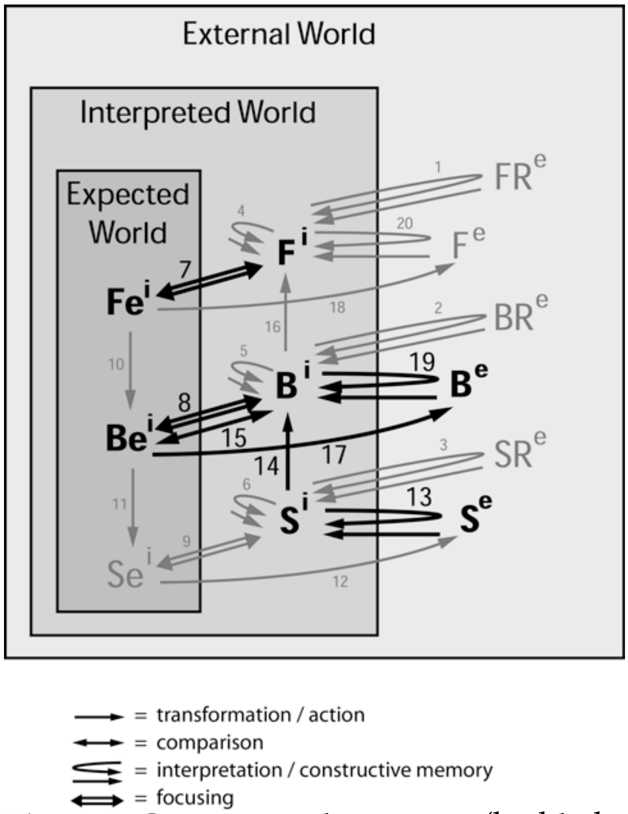

Figure 9. Concepts and processes (highlighted) in reactive affordances

Pre-processing for reactive affordances includes selecting from among alternatives to formulate Fe^i (process 7 in Figure 9) or Be^i (process 8). Alternative Fe^i for doors may include "to allow access to a room" and "to allow exit from a room". A choice between the two Fe^i can influence the selection of alternative Be^i input parameters such as pushing (i.e., "outward" direction) or pulling (i.e., "inward" direction) a specific door. Here, let us assume that the value "outward" is selected for the "direction" parameter of Be^i, based on choosing "to allow exit from a room" as Fe^i. In the stairs example, the person may have the choice between the two specialised Fe^i "to allow fast descent to catch the train" and "to allow descent without spilling your cup of coffee". This has an impact on the selection of a value for "speed" in the stairs' Be^i. Let us assume that a low value is selected to avoid spilling coffee.

Post-processing includes the interpretation of B^e resulting in a new B^i (process 19), and evaluation of that B^i against Be^i (process 15). These processes are necessary to test whether the selected affordance is appropriate. If the affordance "succeeds," no further processes are needed in the scope of that affordance. For example, pushing against the door might produce the expected rotating behavior, which is perceived and evaluated as satisfactory. Walking down the stairs with reduced speed may successfully avoid spilling any coffee.

If the affordance "fails" the test, three possible consequences result. One consequence might be the selection of previously unselected values of input parameters of Be^i, leading to the repeated generation of variants of the same type of affordance (process 8). For example, if pushing against the door is unsuccessful, the person might choose to pull instead of push (i.e., changing the value of the "direction" parameter to "inward") and then to execute and test this new variant of the affordance. This scenario can be viewed as an instance of a discrete control system. In the stairs example, if the person spills coffee while walking down the stairs, the value for the "speed" parameter may be further reduced, and the consequences of this change are then monitored and assessed. This scenario can be viewed as an instance of a continuous control system.

Another consequence of a "failed" affordance may be the reformulation of input parameter values of Be^i by including new yet previously known alternatives (process 8). This change can expand the space of possible affordances. For example, if both possible directions of the force on the door fail, the person might increase the expected amount of force so that it exceeds the initial range. In the stairs example, the person might choose to change the stepping rhythm, thus relaxing a previously fixed input value of the stairs' behavior.

A third consequence may be to modify the selection of Fe^i (process 7) when re-selecting Be^i is not successful. Most commonly, this results in the original Fe^i being dropped. For example, the functions "to allow exit from a room" and "to allow descent without spilling your cup of coffee" may be dropped when the door cannot be opened and the stairs cannot be descended without spilling coffee, respectively.

The class of reactive affordances subsumes the class of reflexive ones. It augments the latter by providing the potential to repeatedly select affordances and to reformulate the ranges of parameter values of expected behaviors.

Reflective Affordances

The processes involved in producing reflective affordances are highlighted in Figure 10.

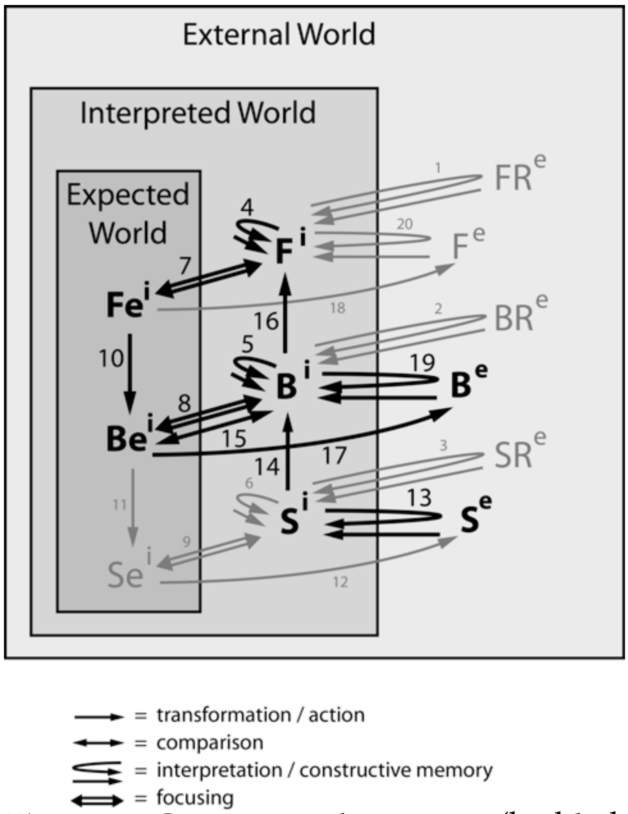

Figure 10. Concepts and processes (highlighted) in reflective affordances

Pre-processing for reflective affordances includes more processes than for reactive and reflexive ones because Fe^i and/or Be^i are not pre-formulated and cannot be selected from existing alternatives. These processes generate expectations depending on the current situation, leading to new or unfamiliar Fe^i and Be^i. In the door example, the person's changing expectations from the "rotating" behavior to a new "sliding" behavior results from a process of reflecting on behavior (process 5 in

Figure 10) and then focusing on that behavior (process 8). Introducing a function of "preventing other people from accessing a room" is a consequence of reflecting on function (process 4) and focusing on that function (process 7). Based on this new Fe^i, the person might then derive the expectation of a "locking" behavior (process 10) that affords a specific rotating motion of a key. In the stairs example, the person might similarly generate the new function, "to allow resting," by reflecting and focusing. A new "seating support" behavior can then be derived from this new function. The input parameters of a reflectively produced Be^i might include specific, fixed values (e.g., "leftward" direction of a force for sliding the door), and/or ranges of values (e.g., variable amounts of force).

Post-processing includes at least the processes of interpreting (process 19) and then evaluating (process 15) an affordance via the associated artifact behavior. In addition, there is the potential for reconstructing expectations by formulating new Be^i and Fe^i, and hence constructing new types of affordances. A frequent precursor of reformulation is the discovery that an observed (i.e., interpreted) behavior can be useful because a new, interpreted function (F^i) can be derived from it (process 16). An example of such a serendipitous discovery is when a sliding door is pushed too far to the side and slips from the end of its sliding rail. This behavior might be interpreted as useful when the door needs to be removed for replacement or repair. Recognizing the utility of this behavior can be represented as deriving the function "to allow easy removal," which may or may not have been intended by the door's designer. Sitting on stairs can similarly lead to the interpretation of a new behavior. For example, assuming that the stairs may have warmed up in the sunlight, their raised temperature can be sensed by sitting on them. This corresponds to a new behavior, which could not have been discovered simply by walking on the stairs (in footwear). A new function, "to allow warming of the human body," may be derived from this behavior.

The class of reflective affordances subsumes the class of reactive ones. It augments the latter by providing the potential for reformulating expected functions and for reformulating expected classes of behaviours. Reflective affordances can shift the space of possible affordances into previously unexpected or unknown regions. Reformulations can occur at any time, potentially moving affordances from being reflexive or reactive to reflective.

Conclusion

Affordances, the short-hand term used to mean "perceived affordances" in this paper, are not fixed properties but the results of dynamic processes that constitute a user's interactions with an artifact. This paper has presented three types of affordances that vary in their ability to deal with the dynamics of these interactions. Reflexive affordances assume a static world that provides a close but rigid fit between action possibilities and artifacts. Reactive affordances allow for variation in the selection of action possibilities, integrating feedback provided by the resulting artifact behaviour. Reflective affordances can generate new worlds of action possibilities through reflection and through exploratory discovery of possible behaviors. The three types of affordances are related through subsumption: Reflective affordances subsume reactive ones, and reactive affordances subsume reflexive ones. Reflective affordances, through their use, tend to become reactive and then reflexive, but there is always the potential for affordances to move the opposite way, too, as a user's situation changes. Thus, the range of use for a design can expand beyond what was intended by the designer.

Our framework is a synthesis of conceptual ideas related to situatedness in designing. While some of these ideas are based on cognitive studies of designing, more work needs to be done toward validating our framework. Representing and experimentally consolidating the three types of affordances can enhance understanding of affordances, which facilitates progress in two broad areas of research.

One area is research into new methods and tools for affordance-based design. For example, existing affordance-based design methods may be extended to include better support for the adoption of creative designs. Creative designs, by definition, provide novel functionalities and often provide novel ways for users and artifacts to interact. "Preparing" the user to easily identify appropriate affordances for a new interaction is crucial for the adoption of a creative design. Our framework presents a set of pre-processing steps that can be targeted when designing, realizing, or marketing creative artifacts.

Another possible research direction is the development of models of user-driven innovation that may be used to stimulate design creativity. These models may be implemented as agent-based systems that simulate possible user interactions and thus generate opportunities for discovering new functionalities and features of a design. A necessary condition for such simulations is the integration of the user's situations before and after an affordance is produced because they allow for recursive interactions that are often the precursor for user innovation. Our description of pre- and post-processing steps can be used as a blueprint for building such a system.

Another area of research that can benefit from our work is the development of affordance-based agent interaction. For example, research in robotics has already started using the idea of affordances in robot control systems, focusing on robot navigation and task execution (Rome et al. 2008). Currently, most of these approaches are based on pre-coded affordances. Using our framework, they map onto reflexive or reactive affordances but not onto reflective ones. Although robots have been built that can explore new affordances of tools by trying out and then grounding possible actions (Stoytchev 2008), these exploratory activities are not driven by changes in the robots' goals and expectations. As a result, the adaptability of the robots in new, unstructured environments is very limited. Current affordance-based architectures for agents in virtual environments are subject to similar limitations. We can identify reflective affordances as a precondition that can lead to more effective deployment of agents in dynamic environments.

Acknowledgements
This work is an outgrowth of research supported by a grant from the Australian Research Council, grant no: DP0559885.

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To appear in *Design Issues*