Modeling Aperture Passage Affordances in ACT-R 3D

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Abstract

In this paper I present a model of aperture passage judgment (judgment of whether an agent can walk through an aperture, rotating shoulders as needed) and performance (initiation and termination of shoulder rotation while walking through an aperture) in ACT-R 3D. The model is adapted from Somers (2016) and represents a first attempt to unify findings across multiple experiments with a single model. The cognitive model is embodied in a robotics simulator, with motor control operated directly by the ACT-R model. The model exhibits an improved fit as compared to Somers (2016), in the same experiment, and a reasonable fit in an additional experiment, in exaggerated conditions.

Keywords: ACT-R; embodied cognition; motor control; cognitive modeling; affordances;

Introduction

Walking through narrow apertures, such as a narrow doorway, may require a shoulder rotation in order to reduce the frontal width of the body to afford passage. From an ecological psychology perspective, an 'affordance' is a property or set of properties (or relations, depending on author) in the environment that specify to an agent what actions are available (Chemero & Turvey, 2007; Chemero, 2003; Stoffregen, 2000; Şahin, Cakmak, Doğar, Uğur, & Üçoluk, 2007; Turvey, 1992). Research in support of affordances has come from a range of domains including stair-climbing (Warren, 1984), aperture passage (Warren & Whang, 1987), reaching (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989), grasping (Tucker & Ellis, 1998), and a number of sports abilities (Fajen, Riley, & Turvey, 2008).

A common theme in affordance research is to identify π-numbers that relate some dimension of the environment (E) with some dimension of body (A) as a ratio: $\pi = E/A$. These π-numbers are typically presented as support for Gibson's notion of *direct perception* (Gibson, 1986). Direct perception is the claim that our actions are not mediated by strong, internal, semantically-laden represenations of the environment. Affordances are, instead, presented to us when the properties of the environment match the action capabilities of the agent.

Aperture passage was first studied by Warren and Whang (1987). In their series of experiments they attempted to identify the π-number that modulates shoulder rotation when walking through apertures. Since Warren and Whang's classical paper, there have been a number of follow-up experiments that either support or extend their findings. Fath and Fajen (2011), for example, modify visual properties in a virtual environment, in aperture passage experiments, to identify a set of visual properties that contribute to the aperture passage affordance. A number of studies have investigated the aperture passage affordance for participants carrying objects (Wagman & Taylor, 2005; Wagman & Malek, 2007; Higuchi, Cinelli, Greig, & Patla, 2006; Higuchi, Seya, & Imanaka, 2012). Higuchi, Takada, Matsuura, and Imanaka (2004) studied passability judgments and aperture passage performance for novel wheelchair users. Finally, Chang, Wade, and Stoffregen (2009) studied passability judgments of people grouped in a dyad. In most cases these authors subscribe, to varying degrees of commitment, to Gibson's theory of direct perception, and therefore offer very little with respect to an information processing description.

In recent work by Somers (2016, 2017), a processing description and accompanying computational cognitive model of the first experiment in Warren and Whang (1987) is provided. Introduced as proof-of-concept for the simulation environment, ACT-R 3D, the aperture-passage model proposes that aperture-passage judgments and aperture-passage performance rely on a comparison of the geometric properties of body schema and the geometric properties of the environment (Somers, 2017). While their model has a reasonable fit to the data in Warren and Whang (1987), given the results in Higuchi et al. (2012) (discussed below), one can anticipate that their model cannot account for aperture passage performance in exaggerated conditions. In this work we adapt their model to account for experiments by both Warren and Whang (1987) and Higuchi et al. (2012).

Aperture Passage Research

Warren and Whang (1987) performed a series of experiments aimed at showing that aperture passage is directly perceived. In their first experiment they had participants walk through apertures of various sizes, rotating their shoulders as needed. Participants were grouped according to size: *large* or *small*. Larger participants rotated their shoulders more than smaller participants when passing through apertures of equal width. When expressed as an aperture-width to shoulder-width ratio, however, group differences were eliminated, suggesting that shoulder rotation is modulated by the ratio between aperture width and shoulder width. This experiment established a critical ratio (π-number) of 1.3 at which participants, regardless of their size, would change from a forward posture to a posture that included a shoulder rotation. This π-ratio, they maintain, is a constant, used by an agent to determine when shoulder rotation is required.

The second and third experiments in Warren and Whang (1987) are aimed at establishing the source of optical information contributing to the passability affordance judgment. In these experiments the authors modify binocular/monocular vision, movement and non-movement conditions, as well as introduce an Ames-room-like illusion. These experiments are meant to establish that the perception of passability is scaled to body units as opposed to absolute size judgments (in some extrinsic dimensions). While these experiments are out of the scope of the models developed for this work, it is worth noting that the conclusions of these two experiments are not entirely incommensurate with the model as the model is agnostic with respect to the source of optical information contributing to the geometric comparison process.

Higuchi et al. (2012) had participants walk through apertures while carrying bars of varying lengths in order to exaggerate the frontal width of participants. While the authors align themselves theoretically with Warren and Whang (1987), with respect to direct perceptions, they also somewhat diverge, offering some insight about the control of rotation. They propose that the central nervous system controls rotation by maintaining a constant safety margin between the agent and the edges of the aperture. By exaggerating the length of the bar they are able to test whether rotation is extremely exaggerated (as would be the case if the π-ratio of 1.3 was used). Their reasoning is as follows:

Consider an agent, 40 *cm* in width. From Warren and Whang (1987) we know that an agent would rotate their shoulders at a π-ratio of 1.3, leaving a 6 *cm* safety margin. If that same person was carrying a bar 100 *cm* in length and rotated based upon the same ratio, then they would create a 15 *cm* safety margin ((100 * 1.3 - 100) / 2 = 15). This over-rotation would be markedly inefficient (Higuchi et al., 2012)

Instead, Higuchi et al. (2012) propose that the central nervous system controls rotation to maintain a consistent safety margin. Assuming a safety margin of 6*cm*, a π-ratio of 1.12 ((100 * 1.12 - 100)/2 = 6) should only be required for safe passage. That is, participants should only begin rotation their shoulders when the ratio between the aperture and themselves (including a bar) is 1.12, and should only continue rotation until they have established a 6*cm* gap between themselves (or the bar) and the edge of the aperture. Their hypothesis predicts: 1) that the amplitude of rotation should become smaller as width increases and π-ratio is maintained; and 2) that spatial margins should remain constant regardless of absolute size or π-ratio.

In their experiment they manipulated aperture ratio and agent widths by having the participants carry bars that modify their frontal width by either a factor of 1.5 or 2.5 (as well as a control condition, bar length 30*cm*). Aperture widths are set to create ratios of 0.9, 1.0, and 1.1 to encourage large rotation. Authors found a main effect of bar length, such that the angle of rotation was smaller as bar length increased (addressing 1). With respect to spatial margin, they found a main effect of bar length.

ACT-R 3D

ACT-R 3D (Somers, 2016) is a time-synchronized simulation environment for the Python variant of ACT-R (Stewart & West, 2006) that consists of a middleware, a camera class, vision module, motor module, as well as a humanoid robot. The ACT-R 3D middleware is time-synchronized with the Mobile OpenRobots Simulation Engine (MORSE) (Echeverria, Lassabe, Degroote, & Lemaignan, 2011; Echeverria et al., 2012).

Vision ACT-R 3D adds a new camera class to MORSE, Geometric Camera, that provides a single, structured, retinotopic geometric description of the scene from the perspective of the agent. On the ACT-R side, an updated vision module, inspired by the SOS Vision System (West & Emond, 2002) in Python ACT-R, which makes accessible 'features' of the environment to the agent (the agent has no access to object labels). Currently the vision module has algorithms for detecting *obstacles* and *openings*. Requests to the vision module from the ACT-R production system are parameterized in order to filter information top-down. For example, when given a request for an *opening*, chunks that describe the minimum size of the opening are used as parameters for the request. If multiple features match the request (e.g. there are multiple openings), the returned chunk is selected based on a weighted random choice, weighted by a *salience* factor, as described by West and Emond (2002).

Motor Control The motor module in ACT-R 3D maintains a hierarchical, symbolic and numerical representation of body parts (currently only the ones being modelled). Each body part has degrees of freedom represented by minimum and maximum values on axes of rotation. As the agent moves its body, the minimum and maximum values achieved are stored in declarative memory, functioning as body schema. (Schwoebel, Branch Coslett, & Buxbaum, 2001; Schwoebel & Coslett, 2005; Coslett, Buxbaum, & Schwoebel, 2008). The motor module also includes functionality to provide proprioceptive feedback to estimate 3D body dimensions in a given posture. How the representations are achieved are currently beyond the scope of the module and is implemented with a measure of the agent's bounding box. The bounding box values are stored with the body schema in declarative memory.

Further details about the time synchronous middleware, the Geometric Camera, vision module, motor module, as well as the simulated robot are available in (Somers, 2016).

Geometry-Based Affordances Theory

Presumably due to the theoretical commitments of ecological psychology, research into aperture passage (Warren & Whang, 1987; Wagman & Taylor, 2005; Higuchi et al., 2012; Fath & Fajen, 2011) is generally sparse with respect to an overall information processing description. Warren and Whang (1987), for example, discuss optical information that might contribute to a passability judgment but miss critical details about cognitive control of the overal amplitude of rotation. Alternatively, Higuchi et al. (2012), suggest that the central nervous system maintains a safety margin between the shoulders and the edges of the aperture (which is a theory explored here), but do not offer a theory about the processes or representation involved.

The model presented in this work represents an instantiation of geometry-based affordances presented in (Somers, 2017). At a functional level, the theory proposes that a certain class of affordances are realized by an agent as a result of a comparison process that compares the geometric properties (width, depth, height) of some feature in the environment and the geometric properties of a current or stored body schema. For more details regarding geometry-based affordances and evidence of the role of body schema, see the work by (Somers, 2017).

The theory/model proposes four phases: 1) a body schema encoding phase, 2) passability judgment phase, 3) rotation initiation, and 4) rotation completion. The four phases are described below.

Body Schema Encoding Phase The body schema encoding phase occurs pre-experiment as part of the agents life. As instantiated in ACT-R 3D, body schemas are stored when a rotated joint reaches its minimum or maximum rotation along the principle axes of rotation. In the simulations, once a simulated robot is generated (according to the size constraints for the experiment), the robot performs shoulders rotations in each direction multiple times to encode the body schema in declarative memory.

Judgment Phase One of the processes not discussed in aperture passage literature is that passability judgments rely not only on the current frontal width but also, potentially some future frontal width, after the shoulders have been rotated. A π-ratio simply cannot account for passability judgments without also introducing either a representation, association process, or simulation process. The judgment phase in this theory/model results from two possible cases. In the first case, body geometry is estimated from a body schema of the current posture, and is used top-down in a visual search for an aperture of appropriate size. If the vision system is able to return a feature in the environment that meets those constraints, the returned aperture is deemed 'passable'. If no environment feature is returned by the vision system, the second case proceeds.

In the second case, a (potential) series of memory requests are made for stored body schema that closely match the current body posture (e.g. standing, no shoulder rotation) and the current action capabilities (e.g. walking) but relaxed in an increasing number of postural details. In the case of aperture passage, memory requests would be for a posture that affords walking, allowing for variation in torso posture (such as shoulder rotation). If a suitable schema is returned, the geometric properties of that schema are used top-down to filter the visual results in the manner described above.

Rotation Initiation Another aspect of performing aperture passage not discussed in the literature is how the rotation is initiated. In this phase, the agent is already walking towards the aperture, and in the model, rotation is initiated when the bottom-up vision system is triggered by the proximity to the aperture. When the edges of the aperture are within a multiple of the agent's rotation radius, the vision system pushes information into the visual buffer, and the agent responds by carrying out a motor plan. The body schema retrieved in the *judgment* phase is maintained in working memory, and used at this point as the motor plan.

Rotation Completion The theory proposes that rotation completion is the result of a moment-to-moment comparison between body schema and optical information about the aperture. This is, to some degree, similar to the theory in Higuchi et al. (2012). The moment-to-moment comparison continues until frontal width of the agent is less than the width of the aperture. Although the body schema retrieved in the *judgment* phase, of fully rotated shoulders, was used as a goal state for the motor module, the agent need not always rotate the shoulders maximally. In other words, the goal state of the motor system was to fully rotate the shoulders, but a moment-to-moment visual update limits the rotation as a result of the comparison process. It is in this process that the current model differs from that of Somers (2016). In particular, the model presented by Somers, inspired by (Warren & Whang, 1987), multiplies the current body schema by a constant to overestimate body width. The model presented in this work favors a comparison process that maintains a safety margin, following the findings and theory of Higuchi et al. (2012).

Model and Experiments

In Somers (2016), the author used the same metric for passability judgment as for rotation completion. That is, their model ended rotation when it was determined that the the agent's frontal width, multiplied by a constant (1.139), was less than the width of the aperture. Given the experimental findings in (Higuchi et al., 2012), however, one can fully expect that the model would over rotate in exaggerated agent-width conditions, especially considering their model exhibited a mild over-rotation in large aperture conditions. In the following we present changes to the model in Somers (2016) and run experiments to for both Warren and Whang (1987) and Higuchi et al. (2012).

Model

The model described in this section goes through the four steps described above: body schema encoding, judgment, rotation intitation, and rotation completion. One of the main factors in producing measurable behavior (rotation degree) is the temporal dynamics of the model. The temporal constraints imposed on the model due to the production system, motor module, and the vision module affect, in particular, when the model will initiate or terminate rotation, creating a source of variability. That said, the kinematics of the simulated-robot agents also has a major affect on degree of rotation.

One of the main assumptions across all models is that they rotate with a constant, instantaneous velocity of 120°per second. The only known aperture-passage study to report on the kinematics of shoulder rotation is from Fath and Fajen (2011), where participants are immersed in virtual environments. Fath and Fajen reported participants initiating rotation between 0.5 and 0.7s before reaching the aperture with rotation degree varying from approximately 20°and 60°. A parameter search was conducted with approximate values (from literature) and a rotation rate of 120°per second (the upper bound as described in Fath and Fajen) was used in all models. This is the same rotation rate used in the model by Somers (2016).

The other kinematic assumption in the model that has a major impact on the rotation prediction is walking rate. Warren and Whang (1987) provide a set of average walking rates in the four condition of their first experiment of: 1.29 m/s and 1.28 m/s (small vs. large) *normal* speed conditions and 1.61 m/s and 1.77 m/s (small vs large) in the *fast* speed conditions. The simulated robots moved at the average speeds reported in Warren and Whang (1987), according to size and speed, for all experiments.

There are three main parameters that affect the rotation in the model. *RadiusMultiplier* is used by the model to affect when to initiate rotation, bottom-up. The *RadiusMultiplier* parameter was set the same value as in the model in Somers (2016) (3.0). A new parameter was introduced for the purposes of this study: VisionConstant. The *VisionConstant* parameter represents the safety margin in Higuchi et al. (2012) and is set to $3cm$ accordingly ($3x2 = 6cm$). Given those parameters as constants, a parameter search for the parameter *VisionMultiplier* was run. In the model by Somers (2016) the *VisionMultiplier* parameter was used both in the judgment phase and in the rotation completion phase, as a means of over-estimating body width. In this model, the parameter is only used in the judgment phase (to detect apertures) and after a coarse parameter search, for apertures of $40cm$ and $55cm$, *VisionMultiplier* parameter was set to (1.36). Note, this value is similar to the π-ratio of 1.3 found by Warren and Whang (1987).

Experiment 1

We re-ran the experimental conditions from Somers (2016), a simulated version of the first experiment in Warren and Whang (1987). Warren and Whang had participants (group: small vs. large) walk through aperture of different sizes in two speed condition (normal vs fast). They found that participants rotated more in response to smaller apertures, that larger participants rotated more than smaller participants, and faster speed resulted in higher degrees of shoulder rotation.

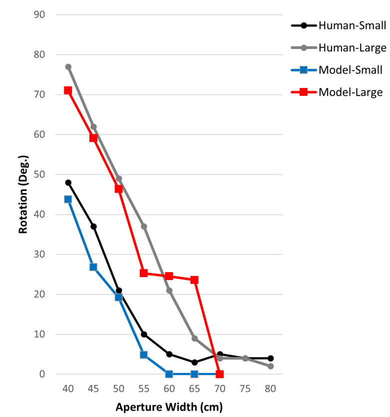

Figure 1: Human vs. Model, rotation angle by aperture width, normal speed. Black and gray line represent small and large human rotation (respectively). Blue and red lines represent small and large model (respectively).

Because there is a floor effect in human data, the models were only run through apertures up to maximum width of $70cm$. All other experimental conditions in Warren and Whang (1987) were re-created as accurately as possible within the simulation environment. In the simulation there were 5 agents per group condition and agent sizes were chosen from a normal distribution centered around the mean human sizes for each group ($40.4cm$ for small and $48.4cm$ for large) with a standard deviation as reported ($SD = 2.0cm$ for small and $SD = 0.7cm$ for large). Agents walked at the average speeds per group reported in Warren and Whang, as described above. There were a total of 20 agents, 10 per size group (large and small). Each agent walked through the apertures 15 times for a total of 15 * 20 (agents) * 2 (speed) * 5 (apertures) = 3000 simulation runs.

Results (Ex 1) Because the original data from Warren and Whang (1987) was not available, limited analysis of fit is provided. A visual comparison between the results in Warren and Whang and the simulation runs are presented in Figure 1 for the slow condition and Figure 2 in the fast condition. A Pearson's correlation on the means (as all data was not available) indicate a fit of 0.98 and 0.91 for the small and large agents in the normal speed condition; and 0.98 and 0.92 for small and large agents in the fast speed condition. A combined RMSE for large and small agents was 8.78°in the normal speed condition and 8.27°in the fast speed condition. In addition to comparative statistics, an ANOVA was run on the model data to see if the same main effects were present in the model as in the human data. Large participants had larger degrees of rotation than smaller participants. Participants rotated more

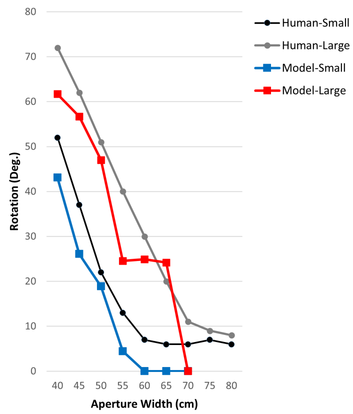

Figure 2: Human vs. Model, rotation angle by aperture width, fast speed. Black and gray line represent small and large human rotation (respectively). Blue and red lines represent small and large model (respectively).

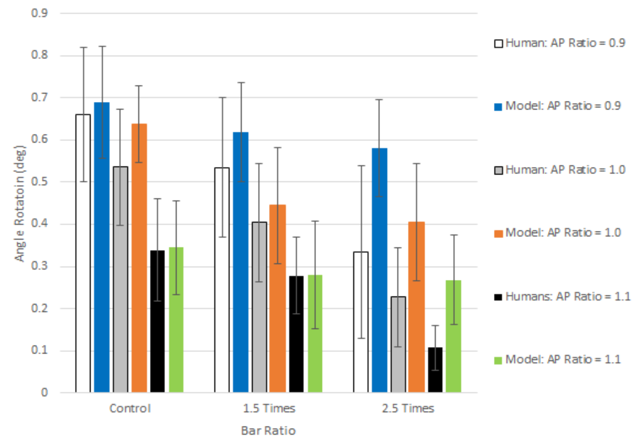

Figure 3: Human (grayscale) vs Model (color) rotation angle for bar ratios: control, 1.5, 2.5 and aperture ratios: 0.9, 1.0, and 1.1.

for narrower apertures. These results are similar to Warren and Whang (1987). Unlike the human data, the model rotated less in fast speed conditions than in slow conditions.

Discussion (Ex 1) Visually the model has a reasonable fit to human data in both the normal and fast conditions. There is evident an over-rotation for large agents (red) at apertures 55*cm*, 60*cm*, and 65*cm* before no longer rotating at an aperture of 70*cm*. Two potential factors (and their combination) could account for this over rotation. First, delays caused by the constraints of the productions system can very easily lead quick rotation inaccuracy. Second, the rotation rate (120°per second) is the high-end of that reported by Fath and Fajen (2011). A more thorough fit for ration rate could have been done but would not have been informative and would have been a parameter fitting exercise without rotation rate data. This model exhibits a better fit to the data than the model presented in Somers (2016).

Experiment 2

The model for the second experiment is the exact same model, with the exact same parameters as in experiment one. The only differences between them are the differences in the simulated robot which reflect the size of participants in Higuchi et al. (2012) and, as described above, the addition of a bar at agent-width ratios of 1.5, 2.5, as well as a control condition (30*cm*). There were a total of 10 agents, who each performed 15 trials of each aperture * bar combination.

Results (Ex 2) Figures 3 and 4 illustrate the mean angle of rotation and mean safety margins for both human and model data. Agents rotated less with larger bars, and rotated less at higher aperture ratios. The effect of bar and aperture ratio are both significant for the model ($ps < 0.01$). A Pearson's correlation indicates a fit of 0.80 for rotation angle and 0.21 for safety margin. Note, however, that the model exhibits a large over rotation at the *2.5 times* bar condition. Excluding that condition, the Pearson's correlation is 0.84 for absolute rotation and 0.89 with respect to safety margin. For the control and the 1.5 bar ratio condition, mean absolute rotation is comparable to human participants.

As shown in Figure 4, the model has a reasonable fit for mean spatial margin in both the control and 1.5 times condition. Agents leave greater spatial margins when carrying larger bars. All effects are significant ($ps < 0.01$).

RMSE, excluding the 2.5 bar condition was approximately 9 degrees of absolute rotation and approximately 2*cm* with respect to safety margin.

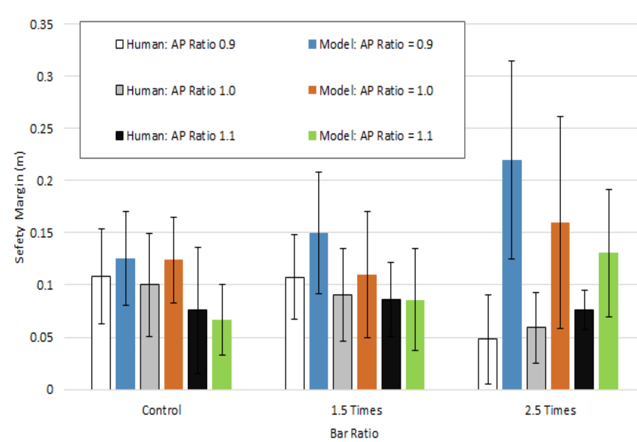

Figure 4: Human (grayscale) vs Model (color) safety margin for bar ratios: control, 1.5, 2.5 and aperture ratios: 0.9, 1.0, and 1.1.

Overall Discussion

Importantly, by implementing this research in a cognitive model, interesting questions are raised about the overall information processing involved in the task. Previous literature has largely overlooked the need to explain how apertures are judged as passable in some future posture. While body schema is one possible answer, and the one explored here, there could be other explanations worth investigating. Proposing body schema also requires a means of storage, a means of retrieval, detail on the representational content, and requisite processes provided in the present work.

Over-rotation is evident in the model across both experiments. It is very likely that the high rotation rate of 120°per second is a large contributor to the over rotation. For example, in the *2.5 times* bar condition of experiment 2, human participants may be exhibiting more caution by either rotating or walking more slowly, and attending to the rotation more thoroughly. The qualitative change in patter in the human data in Figure 4, at the 2.5 condition is at least suggestive that there may be an alternate strategy as compared to the other conditions. It is perfectly plausible that a more thorough parameter search could have resulted in a better model fit, however, to do so would not be well motivated, as the model is constrained by the physical and kinematic properties involved the experiment. Alternatively, there may be low-level implementation details in the in processing for the camera, due to calculations at such an obtuse angle, which could account for both the increase in variance and the higher means in Figure 4. Finally, of course, it could be that the theory in the model is wrong, and an alternate theory and set of processes is required for a unified explanation of the experiments.

The purpose of the research presented here is not to present an absolutely correct model but, rather, to motivate empirical research that could falsify it and, in turn, lead to refinements, or alternatives. Given the reliance on the temporal dynamics of the model, and the relationship to the physical and kinematic properties of rotation, this model motivates a more thorough account of the physical responses of participants, particularly rotation rate, as discussed above. There are, further, more qualitative observations from the model such as rotation initiation that could benefit from empirical measures. From a cognitive perspective, an alternate account of the bottom-up process for initiating rotation as proposed here, could include a more thorough motor plan, or some form of simulation that allows the agent to program the rotation initiation, rotation speed, and, possibly, the rotation termination, without moment-to-moment monitoring.

Finally the role of body schema in a cognitive model presents an interesting research direction. The implementation of body schema for this project, as body configurations stored in memory, is undoubtedly crude, however, it would be interesting to see the development of stronger motor control mechanisms in an architecture such as ACT-R. This is especially true with respect to modeling complex tasks, in complex environments, where processes such as aperture passage judgments enhance agents with capacities to make autonomous action decisions without requiring pre-labeling or apriori knowledge of simulation environments.

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