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A Control Perspective on Imaginal Perspective Taking

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Abstract

This contribution presents a computational cognitive model of imaginal perspective taking (IPT). The model is shown to account for major effects observed in IPT as well as concrete human data from an IPT experiment. Model development was based on the observation that control mechanisms play a central role in IPT performance. In taking this approach, model development and the model itself reveal similarities between tasks which so far have been considered only in isolation, suggesting a common basis for these tasks in terms of computational (control) mechanisms.

Introduction

Imaginal perspective taking (*IPT*, see May, 2004) refers to the ability of humans to judge spatial relations between objects of a previously seen configuration without having sensory access to the configuration at the time of judgment. Although numerous studies (e.g., Hodgson & Waller, 2006; Mou, McNamara, Valiquette, & Rump, 2004; Sholl, 2001; Wang, 2004) have investigated human behavior during IPT, one important aspect of IPT, namely control, has received virtually no attention so far. Since, as shown by Schultheis (2007), control mechanisms can be assumed to be crucial for IPT, neglecting control seems to be a serious shortcoming. The aim of this contribution is to close this gap.

By analyzing available empirical data on IPT, we identified and implemented the control mechanisms involved in IPT. More precisely, we developed a computational cognitive model of IPT which is based solely on control mechanisms. This model is able to account for most of the variance in the human data for a typical IPT task. As a result, the developed model not only stresses the relevance of control to the understanding of IPT, in particular, and spatial cognition, in general, but also constitutes a first computational model for IPT. Moreover, the analysis yielding the employed control mechanisms reveals similarities between the mechanisms underlying (a) IPT and other spatial cognition tasks as well as (b) IPT and task switching. These similarities are considered a particular strength of the model, as they ground the model in independently motivated theoretical principles and at the same time render our model more parsimonious than any model explaining IPT in terms of IPT-specific mechanisms.

In the following we will first give a brief description of IPT, task switching, and the analogies between them (see also Schultheis, 2007). Subsequently, we will detail the theoretical rationale and control mechanisms underlying the developed model. This will be followed by a short exposition of how the model explains the main empirical effects and an application of the model to one particular IPT experiment. Finally, we will discuss related approaches before concluding with issues for future work.

Imaginal Perspective Taking & Task Switching

Imaginal Perspective Taking

In a typical IPT experiment, participants have to memorize a configuration of objects in a certain environment (most often a room). Then participants are blindfolded and often also deprived of any auditory input apart from the experimenter's instructions. In this state the participants are asked to point to objects of the learned configuration from (imaginal) perspectives which differ from the perspective defined by their bodily orientation and position. The to be taken perspective can differ from the bodily one only in orientation, called (imaginal) *rotation*, only in position, called (imaginal) *translation*, or in both. For example, in the case of an imaginal rotation the participant would be asked to indicate the direction to one object x as if facing another object y. In imaginal translation the participant needs to indicate the direction to x as if standing at y. The object to point to is often termed *target*. Usually measured are the time it takes participants to give the pointing response and the pointing error, that is, the deviation of the indicated and the actual direction to the target.

The following main effects on these two measures have been observed in IPT studies: Pointing from an imaginal perspective is more difficult (i.e., takes more time and leads to larger pointing errors) than pointing from the bodily perspective (e.g., Farrell & Robertson, 1998). Rotations are more difficult than translations (e.g., Sholl, 2001). The difficulty increases with increasing angular disparity between the pointing direction from the bodily perspective and the pointing direction from the imaginal perspective (May, 2004). Giving the participants time to prepare for the imaginal perspective before presenting the target reduces the difficulty, but pointing is still more difficult from the imaginal than from the bodily perspective (e.g., Sohn & Carlson, 2003).

Task Switching

The ability of humans to change the task they are currently working on has been investigated intensely in the *task switching* paradigm (see Monsell, 2003). In this paradigm participants have to work on a succession of comparatively simple tasks such as adding or multiplying two digits. The defining characteristic of task switching studies is that the task the participants have to work on repeatedly and frequently changes during the experiment. Furthermore, in most of the task switching studies the stimuli and responses are *bivalent*, that is, the same for the different tasks. For example, in the experiment by Sohn and Anderson (2001) participants had to work on pairs of digits and letters with two possible tasks: Either judge whether the digit is odd or even or judge whether the letter is a consonant or vowel. The judgment had to be indicated for both tasks by either pressing the "z" or the "/" key on a computer keyboard. As in IPT, reaction time and errors are the main focus of analyses in task switching studies.

Generally, the following effects have been observed in task switching experiments (see Monsell, 2003, but also, e.g., Meiran, 2000; Sohn & Anderson, 2001): First, task execution is more difficult (i.e., slower and more error prone) just after a task switch. This decrement is called *switch cost*. Second, switch cost can be reduced if the participants are allowed to prepare for a change of task(s). Third, preparation for a switch does not eliminate switch cost completely. The cost remaining after preparation has been termed *residual cost*.

Analogies

Several analogies hold between task switching and IPT. These analogies become apparent when assuming that different perspectives correspond to different tasks and the bodily perspective corresponds to the previously executed task. Framing IPT this way reveals that IPT—as task switching—uses bivalent stimuli, because targets (the objects to point to) and responses (pointing to the target) are the same for all perspectives. In addition, IPT exhibits a "switch cost" for taking a perspective different from the bodily one and preparation can reduce but not completely eliminate this switch cost.

This similarity of IPT to task switching suggests that a considerable part of IPT performance can be assumed to arise from the working of control mechanisms, since task switching is generally agreed to depend heavily on control facilities. Furthermore, the control involved in IPT might bear resemblance to the control involved in task switching.

Based on these considerations we developed a computational model of IPT in terms of control. This model will be detailed in the subsequent section.

Computational Analysis and Model

IPT as Task Switching

Despite considerable differences regarding the particulars (computational) models of task switching such as the models developed by Meiran (2000), Sohn and Anderson (2001), and Rubinstein, Meyer, and Evans (2001) generally assume that the observed task switching performance is the result of the combined effect of two distinct mechanisms. Furthermore, these models all suggest that one of the mechanisms is responsible for that part of the switch cost which can be eliminated during preparation, whereas the other mechanism is responsible for the residual cost. Although both mechanisms have been termed and implemented differently in the models, the gist of these terms and implementations is the same across models and associated with stimulus ambivalence and response selection. More precisely, the mechanism underlying the reducible cost seems to be related to stimulus disambiguation, that is, to determine how the stimulus is to be interpreted or which part of the stimulus to attend to. The idea is that a certain way of perceiving / interpreting the stimulus is associated with each task and the current mode of perception / interpretation is in accord with the previously executed task. In case of a task switch this mode has to be changed to conform to the new task. The mechanism underlying the residual cost, on the other hand, seem to be related to the influence the previously executed task has on the inclination to select certain responses. Thus, task switching can be viewed as consisting of two components, where the first is associated with stimulus disambiguation and the second is associated with response selection.

Based on the analogy of task switching and IPT a similar two component structure can be assumed to underlie performance in IPT. This is not to say that the processes of disambiguation and response selection involved in IPT are identical to those in typical task switching settings. For example, whereas switch costs in task switching are on the order of 50 - 100 ms, "switching" from the bodily to an imaginal perspective might take several seconds. Consequently, the components of disambiguation and selection in IPT seem to be realized differently than in task switching. How these two components might be conceived of in the scope of IPT and what the underlying mechanisms are, will be discussed in the next two sections.

Stimulus Disambiguation: Reference Frame Selection To be able to point to the target in the IPT task the symbolic target description given by the experimenter (e.g., "point to the phone") has to be re-represented as an egocentric pointing direction. Since this direction is dependent on the perspective taken, different perspectives afford different target representations and, thus, the stimuli employed in IPT are ambiguous. Moreover, disambiguation is a prerequisite for accurately performing on the IPT task. Without successful disambiguation the symbolic target description would in most cases be re-represented incorrectly leading to an incorrect pointing response. Consequently, stimulus disambiguation seems to be a crucial mechanism for successful IPT.

We propose that it is reference frame selection which underlies stimulus disambiguation in IPT. To see this, consider a typical IPT trial where a person has to point to a target from an imaginal perspective. The only source of information for determining this direction is the person's memory of the object configuration, because she has no sensory access to the configuration during IPT. In accord with a number of studies (Mou et al., 2004; Sholl, 2001; Waller, Montello, Richardson, & Hegarty, 2002), we assume that the enduring memory representation which is used during IPT consists of a network of nodes (i.e., object representations), where the links between the nodes represent directions between the objects represented by the nodes. To make use of such a representation, a reference frame is needed which defines a reference direction with respect to which the inter-object relations can be interpreted and experimental evidence (e.g., Hodgson & Waller, 2006) suggests that any such memory representation stores a certain reference direction in addition to the node network. Since the employed reference direction determines all inter-object relations, selecting a reference frame amounts to choosing a certain target direction interpretation, that is, by selecting a reference frame the stimulus can be disambiguated in IPT. Put in terms of the analogy of task switching and IPT, the reference frame is the mode of perception / interpretation which is associated with each task (i.e., each perspective). Accordingly, in a typical IPT trial the mode has to be switched / shifted from the reference frame of the bodily perspective (the previous task is always the bodily perspective; see above) to the reference frame of the imaginal perspective.

Viewing stimulus disambiguation as reference frame selection reveals similarities of IPT to other spatial cognition tasks. In particular, the use of spatial terms such as "above" or "right" has been shown to involve reference frame selection as one important step (Carlson, 1999). Based on this strand of research Schultheis (to appear) has developed a computational model of reference frame selection. This connectionist model consists of a number of units representing different reference frames or, more precisely, reference frame characteristics such as direction or orientation. Via bottom-up and top-down input connections these units are activated to a certain level. Subsequently, all activated units indirectly compete via shunting models until the mutual relation between the competing unit's activation reaches a certain threshold. This threshold is a free parameter of the model and determines how exclusively the reference frame characteristic represented by the unit with the highest activation is retained in the output of the model (see Schultheis, to appear, for model details).

Since IPT seems to rely on reference frame selection, we employed the just described model as the mechanism underlying stimulus disambiguation in IPT. For any IPT trial, stimulus disambiguation by reference frame selection takes place as follows: The reference frame of the bodily perspective and the reference frame of the imaginal perspective will activate certain units in the model. If the imaginal perspective is different from the bodily perspective they will activate different units which then compete until the criterion is reached. As an additional factor the reference frame stored with the node network (see above) will also activate one of the competing units sometimes facilitating and sometimes hampering the selection process. The number of iterations until competition terminates is assumed to be proportional to the time participants need to disambiguate the stimulus.

Response Selection: Response Priming The residual costs in task switching are generally thought to arise from priming. In all of the discussed models of task switching (Meiran, 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001) it is assumed that executing a certain task in one trial will lead—in some form or the other—to the priming of stimulus response mappings relevant to this task. More precisely, all of the models assume that stimulus response mappings for tasks are held in working memory and primed to be more selectable on subsequent trials.

Again drawing on the analogy of task switching and IPT we propose that the second component of IPT is also arising from priming effects. However, due to the results of Wang (2004) it did not seem justified to adopt the priming mechanisms proposed in task switching models as they stand for IPT. Wang (2004) showed that the response effects in IPT seem to arise from rather low-level motor mechanisms. This suggests that (a) priming of working memory representations in the case of IPT is inappropriate and (b) not stimulus response mappings but only the motor responses are primed.

Based on these assumptions we developed a new computational model. This model better corresponds to the experimental results of Wang (2004), while at the same time keeping with the idea of priming as the main mechanism. Our model consists of an array of units which are thought to represent cells in the motor cortex. These units are sensitive to certain directions, such that (a) each unit is maximally activated by one particular direction, the *preferred direction* and (b) activated to a lesser extent by similar directions. More precisely, each unit is thought to respond according to a Gaussian tuning curve which is centered at a cell's preferred direction. The variance of this tuning curve σ is assumed to be a free parameter but the same for all units (see Figure 1).

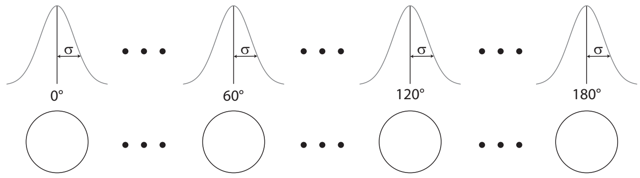

Figure 1: Array of motor units (four examples shown) with their tuning curves. The numbers between each curve and unit signify this unit's preferred direction in degrees.

If in the scope of IPT the pointing direction has been determined, this direction will activate the corresponding motor unit. Once any motor unit is activated to its maximum which is defined as the density of the Gaussian tuning curve at the preferred direction, the corresponding pointing response will be selected and executed. It is further assumed that the time it takes to activate any motor unit to its maximum (i.e., the time to select the corresponding pointing response) is proportional to the relation of a motor unit's preactivation and maximum activation. The lower the preactivation of a motor unit, the longer it will take to select and execute the corresponding response. It is by preactivation of the motor units that priming exerts its influence on the time necessary to perform IPT.

As in task switching, priming is thought to arise from the previously executed task. Since in IPT the previously executed task corresponds to pointing from the bodily perspective (see above), the pointing directions from the bodily perspective should somehow prime the motor units when pointing from an imaginal perspective. We propose that such priming stems from the working of a special representational system for space which has been termed *perceptual-motor system* (e.g., Sholl, 2001). This system continuously keeps track of the directions from a human to different objects in the environment, that is, on a motor level, the direction to different objects is continuously available. Thus, if the target in IPT is presented, this target can activate—on a motor level—the motor unit corresponding to the direction to this target. However, this unit will only be partially activated, because it is not the goal of the participant to point in this bodily defined direction. Furthermore, not only this motor unit, but also motor units with a similar preferred direction will be partially activated. More precisely, due to the tuning curves the activation of a motor unit will be proportional to the similarity of its own preferred direction and the bodily direction to the target.

To sum up, the two proposed components of our IPT model interact in the following way: After the to be taken perspective has been presented, stimulus disambiguation in the form of reference frame selection takes place. When selection is finished and the target has been presented (a) the target direction from the imaginal perspective is determined using the selected frame and the existing memory representation, (b) the corresponding motor unit will be activated, and (c) response priming will add to the activation of the relevant motor unit. Once any motor unit is activated maximally the corresponding pointing response is selected and executed.

To prove that this model constitutes a satisfactory account of IPT, we will both in the following section explain how the model accounts for the main IPT effects and in the section after next show the model's ability to simulate human IPT behavior by applying it to one concrete IPT experiment. In thus evaluating the model we will concentrate on reaction times, since these have been the focus of the presented analysis. However, as the section "Challenges" will explicate, the mechanisms in the model easily allow extending the modeled domain to the errors made by participants in IPT.

Explained Effects

Difficulty of IPT According to the model, longer response time for pointing to a target from an imaginal perspective than for pointing from the bodily perspective has two causes. The first is stimulus disambiguation. If the target direction has to be judged from the bodily perspective, the bodily direction and the imaginal direction coincide and thus will activate the same unit in the reference frame selection mechanism. If the two directions do not coincide, they activate different units and, thus, both the desired direction will be activated less and an undesired direction will be activated more than in pointing from the bodily perspective. As a result, the initial difference between the unit activations will be less when bodily and imaginal direction do not coincide and therefore the competition will take more iterations (i.e., more time) to terminate. The second cause is response priming. As detailed above, motor units will be primed by the perceptual-motor system. This priming will be—due to the tuning curves—be strongest for that motor unit which has a preferred direction identical to the direction of the target from the bodily perspective. As a result it will take more time to activate the response from the imaginal perspective than from the bodily perspective adding to the slower response time in this condition.

Difficulty of Rotations One important aspect of imaginal translations is that the reference direction for the resulting imaginal perspective is the same as for the bodily perspective. Accordingly, during stimulus disambiguation the bodily and imaginal direction activate the same unit in the reference frame selection mechanism which results in lesser iterations until competition termination and, thus, imaginal translation are faster than imaginal rotations.

Difficulty Increases with Disparity This effect is owed mainly to the response priming mechanism. As already said, the response direction from the bodily perspective will be primed most. In particular, due to the tuning curves of the units in the response selection mechanism, any response unit will be so much more activated—by virtue of priming—the closer the unit's preferred direction is to the target direction from the bodily response. Thus, with increasing disparity between the bodily and imaginal target direction the priming activation for the imaginal target direction will decrease. Since lower activations entail more time to fully activate a unit (see above), response time will increase with increasing disparity.

Difficulty Can Partly be Reduced by Preparation The information processed during stimulus disambiguation in IPT is (a) the bodily orientation, (b) the direction stored in memory, and (c) the imaginal orientation. Since (a) and (b) are available anyway, stimulus disambiguation can start as soon as the imaginal orientation is known. Moreover, the availability of the necessary direction for disambiguation (namely the imaginal orientation) does not depend on the availability of the target. Given advance information on the imaginal perspective to be taken, identification of the reference direction can start and proceed prior to target presentation. The effect of response priming, on the other hand, can only take effect after the target is known. Without knowing the target the pointing direction cannot be computed and, consequently, the motor units cannot be activated. Thus, difficulty can partly (due to disambiguation), but not completely (due to response selection) be reduced by preparation.

Model Application

In further evaluating the model we applied it to the data from experiment 3 of May (2004). This experiment seemed to be especially suited, because it is one of the few studies which systematically varied preparation time as well as angular disparity of pointing responses in both imaginal translations and imaginal rotations. In this experiment participants were allowed to learn and memorize an object configuration for 10 min. After learning they had to point to different targets from different imaginal perspectives while standing in the center of the objects. Participants had no sensory access to the configuration during pointing. The to be taken imaginal perspectives were either translations or rotations resulting in an angular disparity of 22.5°, 67.5°, 112.5°, or 157.5°between the target pointing directions from the bodily and the imaginal perspective. Furthermore, each IPT trial presented first the to be taken perspective and then, after a variable SOA of 1, 3, or 5 sec, the target. This design resulted in 24 different conditions for each of which pointing latency and pointing error were measured. As already said, we will concentrate on the latency data in modeling human behavior in this experiment. Accordingly, in modeling we will assume that both stimulus disambiguation and response selection will yield correct results. For stimulus disambiguation this means that in each trial the imaginal orientation will be selected as the reference direction, that is, in each trial the unit representing the imaginal orientation will initially be higher activated than any other of the competing reference direction units.

To model the data from May's experiment we employed the reference frame selection mechanism from Schultheis (to appear) nearly unchanged. In particular, we adopted the same maximum overall activation of the competing units, that is, the sum of the activation of all competing units was restricted to be not above 10. The only thing we changed was the gating criterion which was set to 10.

Given this setup, the model had three free parameters: First, the amount of activation initially received by the unit representing the imaginal reference frame direction. Second,

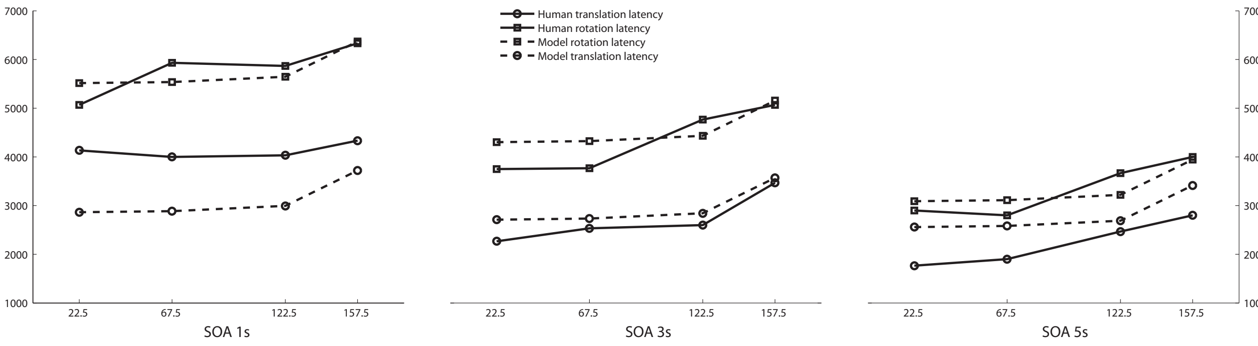

Figure 2: Empirical (May, 2004) and model latencies in ms. The x axis shows angular disparity in degree.

the amount of activation initially received by the unit representing the bodily reference frame direction. Due to the restriction of a maximal activation of 10, the initial activation for the reference frame direction stored with the memory representation was automatically determined by estimating the other two initial activations. Third, the variance of the tuning curves in the response selection mechanism.

The first two were estimated from the latency data of experiments 1 and 2 of Mou et al. (2004) and the third parameter was estimated from the to be modeled data of May (2004). We chose to estimate the first two parameters from a different data set, since this constituted a more rigorous test of the model: With only one parameter to fit 24 data points, a good model fit lends strong support to the validity of the employed mechanisms. The reason to utilize the particular data set of Mou et al. (2004) is that it is one of the few studies which systematically investigated the differential influence of the bodily reference direction and the reference direction stored in memory on IPT latencies. The initial imaginal, bodily, and memory reference frame direction activation was estimated to be 5.7, 3.182, and 1.118, respectively, resulting in a correlation of $r = 0.89$ between human and model data for experiments 1 and 2 of Mou et al. (2004). These parameter values indicate that the influence of the bodily direction is larger than the influence of the direction stored in memory.

Utilizing these activation values we estimated the variance of the tuning curves of the motor units from the data of May (2004). The variance was found to be 1.04. The modeling results using this variance and the corresponding human data for all 24 conditions of the experiment are displayed in Figure 2. The figure shows the reaction times for the different experimental conditions in milliseconds. Model reaction times have been determined by a linear regression of the human data on the raw model data (i.e., iterations resulting from the stimulus disambiguation mechanism plus the relation of the preactivation and the maximum activation of the motor unit; see above). As can be seen from the figure the model data corresponds quite nicely to the human data resulting in a correlation of $r = 0.89$. Note again that this fit of 24 data points was achieved by estimating only one parameter which indicates the appropriateness of the employed mechanisms.

Challenges

Although the model can reasonably account for main behavioral effects found in IPT, there are several aspects of the model which require further considerations.

For example, modeling has so far concentrated on latencies disregarding the effects IPT has on pointing error. Yet, the mechanisms employed in the model seem to be suitable to also account for accuracy data. According to the model pointing error can arise either from stimulus disambiguation or response priming. Regarding the former, depending on the height of the gating criterion, the output of the selection mechanism need not correspond to one of the directions which have competed, but to a weighted combination of these. The lower the criterion the stronger the influence of all competing directions on the final output will be. In terms of IPT this means that with a low(er) criterion the selected direction will be the imaginal direction shifted towards the bodily direction. Since the pointing direction is based on the selected reference direction, a shifted reference direction will lead to an erroneous pointing direction. Regarding response priming, the pointing response based on the bodily direction will have activated other motor units representing a similar response. A response from the imaginal perspective will activate another motor unit and with it also units between the bodily and the imaginal pointing direction. Assuming noisy activation processes, one of these intermediate motor units may reach its maximum first and thus an erroneous response might be given by the participant. Both mechanisms predict errors to occur in the form of a shift of the imaginal response to the bodily response which is in accord with the observation of May (2004) that this kind of error is the most frequent one.

A second aspect is that the response selection mechanism in its current form, explains selection effects by positive priming. Thus, bodily based responses can influence IPT performance only by facilitating but not by hampering imaginal based responses. This seems to run counter to experimental results indicating that the bodily perspective can both facilitate and interfere with the imaginal perspective (Waller et al., 2002). On the basis of the presented analysis it is not clear whether the proposed mechanisms are able to account for the relevant empirical effects. Consequently, one major point of consideration in the further development of the model will have to be the clarification of this matter.

Related Work

Other computational accounts related to human perspective taking have recently been proposed. Hiatt, Trafton, Harrison, and Schultz (2004), for instance, have developed a system which allows a robot to disambiguate a spatial utterance by taking the perspective of a human speaker. Although the task of the robot is similar to IPT, the developed computational account does not seem to be a cognitive model in the strong sense. Instead of trying to most accurately account for human behavior, the focus has been more on building a technical system which is able to conveniently interact with a human. In contrast, Gunzelmann and colleagues (see, e.g., Gunzelmann, Anderson, & Douglas, 2004) have developed detailed and accurate computational models of human behavior, but the task they used (and modeled) differed in important aspects from IPT. For instance, a map-like view of the object configuration was available to the participants during the whole task.

As a result, our model differs from these two approaches in both considering IPT and trying to accurately account for human behavior and, thus, our model constitutes a first computational model of human cognition in IPT.

Conclusion

In this contribution we presented a computational model of human cognition and behavior in imaginal perspective taking. Model design was motivated and governed by a previously observed analogy of task switching and IPT. Not only did this analogy indicate the importance of control for IPT, but also suggested that stimulus disambiguation and response selection are two important components in IPT. Both components have been realized by separate mechanisms in the model. In particular, the mechanism used for stimulus disambiguation—namely reference frame selection—was not developed specifically for modeling IPT, but has been drawn from research on the use of spatial terms. The resulting model has been shown to be able to account for main effects observed in IPT as well as concrete human data from an IPT experiment.

Besides constituting a first computational account of IPT, the model points out similarities between IPT and task switching as well as IPT and spatial term use. As a result, one main contribution of the model is to highlight commonalities of seemingly different tasks, that is, revealing possible fundamental mechanisms governing human cognition, in general, and spatial cognition, in particular.

Future work will concentrate on extending and refining the proposed model with respect to, for example, error modeling and interference in response priming. Furthermore, we plan to explore the suitability of the reference frame selection mechanism for other spatial cognition tasks.

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