Optimal versus heuristic planning of object manipulations: A review and a computational model of the continuous end-state comfort effect

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Abstract

Human beings select actions that facilitate the execution of later actions. For example, humans tend to select grasps that ensure that forthcoming object manipulations end in a comfortable posture ("end-state comfort effect"). Basic experimental results and their explanation within the optimal control framework are reviewed. I conclude that the discrete grasp selection tasks, which are commonly used to study anticipatory planning, leave room for alternative explanations. Moreover, the results of seven experiments employing a continuous grasp selection task seem incompatible with the optimal control (of end-state comfort) account. I introduce the weighted integration of multiple biases (WIMB) model, which accounts for many aspects of the selection of human grasp orientations in continuous tasks. Additionally, it accounts for the precision effect and hysteresis effect. The model shows that the brain may rely on a simple heuristic and does not actually has to anticipate the end-state of a movement to select effective grasps for object manipulations.

Keywords: Grasping, Planning, Anticipation, End-state Comfort Effect, Optimal Control, Weighted Integration of Multiple Biases Model

1. Introduction

Human beings surpass other animals in their ability to make plans – sometimes good and sometimes bad ones – to reach their goals, in a variety of domains and over various time spans. A plan can span several decades; for example, making retirement arrangements early in one's career. Or it can be as simple as the plan to reach for a filled cup of coffee on the desk to kick-start one's career. Despite their considerable differences, both plans have many things in common. A number of actions have to be selected and executed in a specific order. Moreover, which actions are selected early affects which actions have to be executed later on and how easily they can be implemented. For example, opening an account for a retirement plan at a local financial institution may be the easiest possible first step, but if the bank has no branches in other cities, it may be difficult to use it if one moves to another place. Likewise, the cup could be grasped at any position, but if the cup is hot, moving the cup to the mouth may be less painful when grasping the cup by its handle. Finally, to select appropriate actions, one has to take into account future events and the requirements of future actions. For example, to select an appropriate grasp for the cup, one has to anticipate its physical properties, such as weight or temperature, and forthcoming interactions with the cup, such as whether or not the selected grasp enables drinking from it.

Given these similarities, it has been proposed that simple motor acts such as reaching and grasping may serve as a model for goal-directed behavior in general (Grafton, 2010). This notion is further justified by the finding that the execution of simple motor acts depends on and interferes with "higher-level" cognitive processes, such as memory (Creem & Proffitt, 2001; Weigelt et al., 2009). Moreover, basic motor processes have been proposed to contribute to many other human abilities, such as imitation (Gallese et al., 1996), social interaction (Wolpert et al. 2003), or cognition in general (Cruse, 2003). Thus, investigations of the planning of simple actions not only directly inform about motor processes but also about the properties of human goal-directed behavior and planning in general.

Producing and executing a plan requires many abilities. Here, I will focus on how early parts of the plan (i.e., how an object is grasped) are aligned to the demands of later actions (i.e., how the object needs to be manipulated). In the remainder of Section 1, I will review empirical data and discuss the merits and limitations of the optimal planning model. In Section 2, a series of experiments is summarized that is hardly compatible with the optimal planning model. In Section 3, an alternative model is presented and evaluated.

1.1 The Bar Transport Paradigm

The alignment of early actions to later ones has been frequently studied by asking participants to execute short sequential actions, which often have only two components. To isolate the effects of the demands of later actions on earlier ones, the instructions or requirements for the first actions are kept constant (e.g. "grasp the object …") but the instructions for the forthcoming actions are varied (e.g. "… and do X with the object"; see Gentilucci et al., 1997; Herbort & Butz, 2010, 2011, 2012; Marteniuk et al., 1987; Rosenbaum et al., 1990, 1996).[1] It is then observed whether or how the execution of the first action depends on the instructions for the subsequent ones. For example, reach-and-grasp movements may differ in movement speed, finger shaping, or grasp orientation, depending on what a participant intends to do with the grasped object. Such experiments have not only been conducted for object manipulation tasks but also in other domains such as sequential pointing movements (Fischer et al., 1997; Herbort & Butz, 2009; Klein-Breteler et al., 2003), locomotion (Cowie et al., 2010), piano playing (Engel et al., 1997), or tool use (Herbort, 2012). Figure 1 shows two situations in which a cartoon character adjusts his grasping movements to the subsequent actions.

Probably the most influential paradigm to investigate the planning of sequential actions is the bar transport task, which was introduced by David Rosenbaum and his colleagues (1990). In the original experiment, participants were asked to grasp a horizontally oriented bar and place it vertically in an adjacent socket with a specific orientation. This required the participants to rotate the bar either 90° in a clockwise direction or 90˚ counterclockwise. If participants used their right hand, they grasped the bar with a prone "overhand" grip before clockwise rotations but with a supine "underhand" grip before counterclockwise rotations. For left-handed grasping, the pattern was reversed. The results showed that the grasping action was aligned to the subsequent rotation. As these grasp selections resulted in uncomfortable initial arm postures (when grasping the bar) and a comfortable final posture (at the end of the bar rotation), this phenomenon is called the "end-state comfort effect" (cf. Figure 1).

The end-state comfort effect has been studied in a variety of different setups, for example the rotation of handles (e.g. Rosenbaum et al. 1996), control knobs (e.g. Herbort & Butz, 2010; Kelso et al., 1994), or other types of movements (Cohen & Rosenbaum, 2004; Zhang & Rosenbaum, 2008). It has been investigated in bimanual tasks (e.g. Janssen et al.,

[1] The first instruction is often implicit; for example, if it is a prerequisite for executing the second action.

2010; Weigelt et al., 2006), in clinical populations (e.g. Hughes, 1996; Mutsaarts et al., 2006), in different age groups (e.g. Thibaut & Toussaint, 2010), in cooperative tasks (Gonzales et al. 2011; Herbort & Butz, 2012), and even in monkeys (Weiss et al., 2007).

1.2 The Optimal Control Account of the End-state Comfort Effect

Many empirical findings related to the end-state comfort effect have now been gathered. However, relatively little is known about the planning mechanisms that enable such anticipatory actions. The most frequently discussed explanations of the end-state comfort effect have been rooted in the optimal control framework (Johnson, 2000; Rosenbaum et al., 1990, 1996; Schütz et al., 2011; Short & Cauraugh, 1997).

The basic tenet of the optimal control framework is that out of all possible actions that could be used to reach one's goals, those actions are selected that optimize an intrinsic cost function, which is often called the "objective function" or "optimality criterion". The cost function can be a simple criterion (Flash & Hogan, 1985; Uno et al., 1989), which takes into account only a single aspect of the movement or a more complex structure of constraints (e.g. Rosenbaum et al., 2001). Based on this cost function, alternative movement plans are evaluated online and the plan with the lowest costs is selected (e.g. Rosenbaum et al., 1995, 2001).[2] Alternatively, it has been proposed that a control structure learns to associate actual and desired sensory states with those actions that realize the desired states with minimal costs (so called "inverse models", e.g. Herbort et al. 2005; Sabes, 2000; Wolpert & Kawato, 1998). These models have been extended to online planning models that combine inverse model learning with task-dependent constraint satisfaction (Butz et al., 2007). Whereas most current models of action planning focus on individual reaching or grasping movements, the approach has also been extended to sequential (reaching) movements (Fischer et al., 1997; Herbort & Butz, 2007; Hirayama et al., 1993).

The end-state comfort effect is frequently explained with the *optimal planning of end-state comfort model*, which is an instance of models within the framework of optimal control (Cowie et al., 2010; Johnson, 2000; Schütz et al., 2011; Short & Cauraugh, 1997; Weigelt et al., 2009; but see van Swieten et al., 2001). According to this model an (approximately) optimal planning process selects an initial grasp orientation that minimizes the discomfort of the final posture. The optimal planning model is in line with several empirical and theoretical findings. First, it has been found that end-state comfort is a strong determinant of grasp

[2] With "online optimal planning," I refer to mechanisms that select actions among alternative possibilities based on a cost function. Because of the complexity of human movement, planners often merely approximate an optimal movement selection (e.g. Butz et al., 2007; Rosenbaum et al., 1995, 2001).

selection, at least if a task requires accurate object manipulations. Second, grasp selection and subjective comfort ratings are correlated (e.g. Cruse et al., 1993; Rosenbaum et al., 1990). Third, the end-state comfort criterion appears ecologically valid because posture comfort is correlated with movement speed and accuracy (Rosenbaum et al., 1996; Short & Cauraugh, 1999). Fourth, the end-state comfort criterion has been shown to overrule other biases in movement selection (Weigelt et al., 2006). Fifth, the focus on movement (end-)postures as a criterion for movement planning is in line with current models and empirical data on motor planning (Aflalo & Graziano, 2006; Butz et al., 2007; Rosenbaum et al., 1995, 2001). Sixth, the optimal control approach has proven to be a successful framework for understanding simpler actions such as saccades or reaching movements (Berthier et al., 2005; Harris & Wolpert, 1998; Todorov & Jordan, 2002; Rosenbaum et al., 1991; for reviews see Engelbrecht, 2001; Todorov, 2004).

1.3 Several Factors Determine Grasp Orientation Selection

In the previous section, optimal planning of the end-state was presented as a possible explanation for the end-state comfort effect. While this approach is appealing for its straightforwardness and clarity, it certainly is an oversimplification. Several findings show that other factors affect grasp orientation selection besides end-state comfort. One example is the "thumb-toward" bias. Rosenbaum and colleagues (1992) conducted an experiment that required moving and rotating a bar with a marked end. Participants tended to align the thumb with the marked end of the bar, which needed to be aligned with a target stimulus. Additionally, grasp selections foreshadow the direction of an object transportation movement. For example, participants' grasp orientations may depend on whether an object is moved leftward or rightward while being rotated (Herbort & Butz, 2011). Moreover, the accuracy requirements of the task (e.g. Cohen & Rosenbaum, 2004; Short & Cauraugh, 1999) and recent grasp choices (e.g. Kelso et al., 1994) modulate grasp selections. Thus, grasps were not just selected to avoid extreme joint angles but also depended on other, potentially intentional, factors. Finally, it has been shown that habitual factors, such as the personal experience with an object, also affect grasp selection (Herbort & Butz, 2011; McCarty et al., 1999).

In conclusion, end-state comfort accounts partially for initial grasp orientation selections in many tasks but is certainly not the sole determinant of grasp orientation before manipulating an object. To adequately explain initial grasp orientation selection within the optimal planning model, or within the framework of optimal control in general it would be necessary to consider a more complex cost function that takes several variables into account.

1.4 Problems with Empirical Support for the Optimal Planning Model

Besides these abovementioned limitations of the optimal planning of end-state comfort model, the currently available empirical findings leave room for alternative explanations. In most experiments on the end-state comfort effect, the end-state of the sequential action is confounded with the to-be-executed rotation and the effect has been mainly studied using discrete grasp selection tasks (e.g. Janssen et al., 2010; McCarty et al., 1999; Rosenbaum et al. 1990, 1992, 1996; Short & Cauraugh, 1997; Thibaut & Toussaint, 2010; Weigelt et al., 2006). It is questionable whether these studies require the conclusion that end-state comfort, or more specifically the anticipation of properties of the final posture of a sequential movement, is used as a criterion to generate an (at least approximately) optimal movement plan.

One problem with the optimal planning model is that it has been derived from relatively constrained tasks but at the same time it is very general and makes precise predictions. It predicts that all object rotation movements will terminate in, or at least close to, the most comfortable posture.[3] Thus, the optimal planning of end-state comfort model enables us to construct a function mapping any intended object rotation onto a specific grasp orientation within the continuum of adoptable postures. Such fine-grained predictions have been derived mainly from discrete grasp selection experiments, which actually provided a relatively coarse picture of grasp selections (e.g. Janssen et al., 2010; Rosenbaum et al., 1990; 1992; 1996; Short & Cauraugh, 1997; Weigelt et al.; 2006). One the one hand, many of these experiments called for just a small number of different object rotations. Consequently, they tested a limited subset of rotation angles (i.e., points on the x-axis of the function) for which the optimal planning of end-state comfort model is able to make predictions. On the other hand, the discrete grasp selection task offers usually only two highly distinct grasp options to the participant (i.e., two possible values on the y-axis), providing only a coarse-grained comparison with the grasp orientations predicted by the optimal planning of end-state comfort model.

This reasoning can be illustrated by the following example. Consider this alternative model: whenever someone intends to rotate a handle to a specific position, he could base his grasp selection solely on the *direction* of the required rotation, without anticipating or evaluating the posture at the end of the movement. If a (right-handed) person has to rotate a horizontal handle to a vertical position, he may exhibit the end-state comfort effect only

[3] Of course, it is possible that there is no single most comfortable posture but a range of more comfortable postures. However, the wider the range of comfortable postures the less explanatory power the optimal planning of end-state comfort model will have.

because he generally prefers an overhand grip for clockwise rotations and an underhand grip for counterclockwise rotations. In this case, he is not anticipating the final posture during movement planning, hence does not use end-state comfort as a criterion during planning. This example shows how the data pattern in many experiments (e.g. Rosenbaum et al., 1990) could be explained by a much simpler account than the optimal planning of end-state comfort model, because the end-state for the movement is confounded with the direction and extent of the object rotation. However, a more detailed examination of grasp selections may be able to distinguish between alternative accounts. Therefore, experiments that test a larger number of object rotations and that enable participants to choose among a higher number of grasp alternatives are required to put the optimal planning model to the test.

1.5 Short Summary

To conclude, the hypothesis that grasp orientations for object manipulations are generated by an optimal planner that takes into account end-state comfort as a criterion during movement selection can account for many current findings, even though this may be partially due to the constraints of many experimental tasks. To improve our understanding of the mechanisms underlying the end-state comfort effect, we need to move past the limitations of discrete grasp selection tasks and get more detailed information on initial grasp selections and the resulting final postures. One way to extend previous research would be investigating the end-state comfort effect in less constrained tasks. The required object rotation should be varied in a parametric way and participants should be enabled to adopt any grasp orientation before they rotate the object. Ideally, such experiments would provide a function that maps a continuum of object rotations onto a continuum of grasp orientations, and yielding a more detailed comparison of the predictions of the optimal planning model with empirical data. In the following section, I review several studies which strive to provide such tests.

2 Anticipatory Grasp Selections in Continuous Tasks

In this section, I review several studies that examined the end-state comfort effect in continuous tasks, which overcome some of the limitations of the frequently used discrete tasks. These tasks are in principle similar to the discrete tasks but differ in two quantitative aspects. First, the object rotations are varied in a parametric way, probing a larger number of object rotations. Second, the tasks offer more fine-grained measurement of grasp orientations. They not only reveal in detail which initial grasp orientations are selected if the grasp orientation is not constrained by the object but also provide data on the resulting final postures. Thus, these tasks afford a more rigorous test of models of grasp orientation selection.

2.1 Study Selection and Data Extraction

In this review, studies were included that (1) provide data about initial grasp orientation; (2) provide data on final grasp orientation (after the object is rotated); (3) employ objects that could be grasped in more than two ways; and (4) require the object to be rotated, with a pronation or supination of the arm. A literature survey revealed that seven experiments met these criteria: one experiment from van der Vaart (1995), data on healthy participants from two experiments reported in Mutsaarts and colleagues (2006), the results of Herbort and Butz (2010), and three experiments reported in Herbort and Butz (2012). We excluded one object-rotation study in which movement end-states were not reported (Robert et al., 2009) and another from which grasp orientations could not be extracted (Haggard, 1998). Table 1 shows sample size, the specific source for the data used, and other properties of the included experiments. Reported data are averaged over all participants in each experiment.

2.1.1 *van der Vaart (1995)*

In van der Vaart (1995)'s thesis, several rotary input devices were compared. In one experiment, participants were asked to rotate a small circular knob between -120° and 120° in steps of 30°. The knob was grasped between the 3rd and 4th finger, with the hand forming a fist. The forearm supination of the participants was recorded with an optical motion tracker and reported for the moments before and after knob rotation. We obtained our data from van der Vaart's Figure 5.1.

2.1.2 *Mutsaarts et al. (2006)*

Mutsaarts et al. (2006) compared anticipatory motor planning in hemiparetic patients and in healthy controls who were asked to rotate a hexagonal knob between -180° and 180° in steps of 60°. The authors reported how frequently each side of the knob was grasped with the four fingers of the hand, depending on the rotation participants were instructed to carry out. The initial grasp orientation was extracted by weighting the orientations of the sides of the hexagon by the frequency with which each side was grasped with the four fingers. Thus, the grasps 1, 2, … 5, as referred to in Mutsaarts et al.'s Figure 2, were assigned the grasp orientations -120°, -60°, … , 120°. Only data from healthy participants were taken from Mutsaarts et al.'s Table 3 and Figure 3. The grasp orientation after rotation was calculated by adding the instructed rotation angle to the grasp orientation before rotation.

2.1.3 *Herbort and Butz (2010)*

Herbort and Butz (2010) studied the effect of advance information on grasp orientation selections. Each participant had to rotate control knobs between -135° and 135° in steps of 45°, located in front of the participant to the left or right of her midline. The initial and final grasp orientations were recorded with a three-axis accelerometer[4] and were reported in detail in Herbort and Butz's (2010) supplementary material. For this review, the original data were used, pooled over all experimental conditions except the rotation angle.

2.1.4 *Herbort and Butz (2012)*

Herbort and Butz (2012) reported data on grasp orientation selections before rotating a rigid, freely moveable object. In this case, the rigid object was an open cardboard box with a fixed circular handle inside it. The box had to be rotated between -270° and 270° by 90° steps (Experiments 1 and 4) or by 180° steps (Experiment 3). The initial and final forearm orientations were recorded with a three-axis accelerometer and are reported in Herbort and Butz's (2012) supplementary material. In Experiment 1, only the rotation angle was varied. In Experiments 3 and 4, the visual stimulus prompting the rotation and the forearm orientation before the onset of the reaching movement were manipulated in addition to the rotation angle of the box. Both variables showed a significant effect on grasp orientation selections, but each was small compared to the effect of the rotation angle. Thus data from Experiments 3 and 4 were pooled over these experimental conditions for this review.

2.2 Initial and Final Grasp Orientations

The reported experiments present data for different effectors (e.g. hand, forearm), which may contribute differently to the overall rotation of the object. For example, it has been reported that the actual object rotation is accomplished by the combined rotation of the forearm and hand (e.g. Herbort & Butz, 2010) and might depend on the specific task. To account for these possible differences, grasp orientations have been plotted in Figure 2 as a function of 1) the object rotation and 2) the rotation of the effector that was necessary to bring about the required object rotation. The figure shows the initial grasp orientation (top row) and the final grasp orientation (bottom row).

The plots show that in all experiments, the grasp orientation before rotating the object depended considerably on the forthcoming object rotation. Interestingly, the shapes of the plots reveal a discontinuity between grasp orientations before clockwise and counterclockwise rotations. That is, the plots show comparatively large differences between those initial grasp orientations that precede the smallest clockwise rotations and those that precede the smallest counterclockwise rotations. In contrast, differences in the initial grasp orientations between

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[4] An accelerometer can be used to record the orientation of a (static) object with respect to the gravitational field.

small and large rotations in the same direction are comparatively small in many experiments. Additionally—for example, in the data of van der Vaart (1995)—the slope of the plot differs between clockwise and counterclockwise rotations.

The plots also reveal that the end-states of the rotational movements vary considerably between rotation angles in all reported experiments. Thus, while grasp orientation selections tend to reduce the maximal excursion of the forearm, the data do not suggest that movements terminate in or close to a hypothetical most comfortable posture.

2.3 Review Conclusions

This micro-review has shown that a range of experiments, by different research groups using different tasks, have reported strong adjustments of grasp orientation to rotations of a small extent but weak adjustments of grasp orientation to rotations of a larger extent. These results are surprising from the perspective of the optimal planning model because it is hard to explain why comparatively small rotations (e.g. 30° or 45°) result in comparatively strong, even exaggerated, anticipatory pronations or supinations, whereas larger rotations are compensated to a much lesser degree. Even in Mutsaarts et al.'s (2006) Experiment 1, a closer inspection of the data reveals a small discontinuity in the grasp orientation function.[5] In several studies, these results were interpreted as incompatible with the notion that end-state comfort describes grasp orientation selection accurately (Herbort & Butz, 2010, 2012; van der Vaart, 1995; for a similar conclusion see Robert et al., 2009). Indeed, the apparent discontinuity between grasps for clockwise and counterclockwise turns hints at the possibility that the intended rotation direction rather than the anticipated end-state is a key factor in grasp orientation selection.

As end-state comfort alone is not sufficient to explain grasp selection for object manipulation, one might try to reconsider and extend the end-state comfort criterion. In Herbort and Butz (2012), several alternative criteria are discussed. However, none of the criteria under discussion fully accounts for the data. For example, a mixture of initial state comfort and end-state comfort would account for an effect of the intended object orientation on grasp orientation before and after rotation, but not for the discontinuous data pattern. Likewise, the strategy of optimizing end-state comfort if the required initial-state comfort falls below a threshold and trading off initial-state comfort for end-state comfort otherwise would help to understand the data for rotations of a larger extent but would hardly explain the

[5] The slope of the grasp orientation before rotation function is steeper between the -60° rotation and the 60° rotation than between the -180° and -60° rotation or between the 60° and 180° rotation (an 0.75° vs. an 0.46° difference in forearm orientation for a 1° difference in instructed object rotation).

rather strong differences in grasp selections for shorter rotations. Thus, it appears to be hard to describe grasping and object manipulation movements using an ecologically plausible optimality criterion.

3 Optimal Planning Model Revisited

The optimal control framework is a prominent theoretical approach in the motor control literature, one that has proven to explain simpler movements such as saccades or reaches (e.g., Harris & Wolpert, 1998). Nevertheless the optimal control framework in general and the optimal planning model in particular may be limited in the explanations they offer for planning object manipulation movements. There are several reasons for this conclusion.

3.1 Explanatory Value

Although it is possible to find an optimality criterion that would enable the optimal planning model to account for the data, one might ask whether it is desirable. Indeed, there are several reasons to look for alternative avenues of explanation. One is that proposing a suitable but ecologically unmotivated optimality criterion would only provide a circular explanation (cf. Engelbrecht, 2001). The optimality criterion would have to be derived from current data ("According to the data, the optimality criterion must be X") and, at the same time, be used to explain those data ("The data resulted because humans optimize X"). Therefore, such a criterion might be lacking in explanatory value. Moreover, even if an ecologically valid criterion were provided that fits the data, this would inform us why an action is beneficial but would not tell us which mechanisms actually generate the plan.

3.2 Simplicity

A second reason is that the optimal control approach is not an economical account. To be able to generate optimal plans, either computationally expensive online planning processes would have to be carried out or a highly accurate inverse model would have to be learned. While several accounts of (approximately) optimal online planning or inverse model acquisition have been proposed (Butz et al., 2007; Hirayama et al., 1993; Rosenbaum et al., 1995, 2001; Wolpert & Kawato, 1998; Wolpert et al., 2003) and are able to explain simpler movements, such as reaching or sequential reaching, it is unclear whether these models could be extended to account for the generation of more complex action plans.

3.3 Preconditions for Optimal Planning

Beyond the complexity of generating an optimal plan for movements that involve many degrees of freedom, in order to generate at least a good plan it is necessary to make precise predictions of the planned course of action. For example, to select an optimal initial grasp orientation with respect to properties of the final posture, one needs to anticipate the final posture and the costs associated with that posture. However, it is unclear how precisely this information can be anticipated.

Even though it has not been directly studied how accurately the posture after rotating an object can be predicted, some findings hint that this prediction may be difficult to make. For example, forearm rotation does not necessarily map one-to-one onto the rotation of the object. Whereas Herbort and Butz (2010) report that hand and forearm each contribute about 50% to the overall rotation of a fixed knob, in the task employed by Herbort and Butz (2012) the contribution of the forearm to the overall rotation of a freely moveable object was about 75%. The way the arm has to be moved to rotate a specific object may be hard to predict before the onset of the rotation.

Furthermore, studies that reported the kinematics of knob rotations have found that such movements frequently contain corrective sub-movements (e.g. Herbort & Butz, 2010; Novak et al., 2000). Feedback from the hand and from the knob were needed to move the knob to the correct position, suggesting that participants were unable to completely plan the rotation of their arms before the onset of the movement. This suggests that the arm movement required to manipulate the object is partially unknown during planning and thus, the relationship between the end-state of the intended movement and the initial grasp orientation remains uncertain to a considerable degree.

Finally, to select an optimal initial grasp orientation, not only accurate predictions of the movement end-states resulting from various possible grasps would be necessary but also anticipations of the costs associated with these end-states. However, anticipated costs may differ from the actual costs (Johnson, 2000). Johnson asked participants to grasp a bar in various orientations and rate the awkwardness of the posture (motor control condition) but also to prospectively judge how awkward it would feel to grasp a bar with a certain orientation (prospective condition). Even though prospective and motor-control judgments were highly correlated, there were differences between the ratings. Participants' prospective judgments tended to overestimate the awkwardness of comfortable postures and underestimate the awkwardness of awkward postures. Thus, there is also uncertainty in anticipating the costs of different movement alternatives.

In conclusion, the optimal planning account requires a computationally expensive planning process that includes the ability to anticipate the costs of various movement alternatives. However, at least in the case of grasp selection for object rotations, these anticipations seem to have only limited validity. Although the optimal planning model could be extended to account for the data, its possibly limited explanatory value, the assumption of a computationally expensive process, and its preconditions that may not be fulfilled, make the optimal planning model rather unattractive. In the following section, a simple alternative model to explain grasp orientation selection for object manipulation is presented and evaluated.

4 The Weighted Integration of Multiple Biases Model

This section describes an alternative account of grasp selection for object manipulation: the *weighted integration of multiple biases model* (WIMB, Herbort & Butz, 2012). The model aims to show that the pattern of initial grasp orientations reported in Section 2 can be explained by assuming a very simple process that relies neither on the anticipation of movement end-states nor on the associated cost functions. In this section, the WIMB model is briefly described and contrasted with the optimal planning account.

4.1 WIMB Model Outline

According to the WIMB model, the initial grasp orientation is determined by integrating biases provided by different processing pathways into a single grasp orientation. Thus, the model can be expressed mathematically as a simple weighted sum of different postural biases. The weights of the biases may differ depending on the task. As a simple example, consider grasping a control knob for rotation. In this case, two biases are assumed to contribute. One of the biases pulls the initial grasp orientation toward a preferred task-independent orientation, which may be termed the "default" grasp orientation. The other is an anticipatory bias pulling the initial grasp orientation toward a pronated or supinated position, dependent on the intended *rotation direction*. For simplicity, it is assumed that whenever an object is to be rotated clockwise, the second bias pulls toward a specific counterclockwise-oriented grasp, and whenever an object is to be rotated counterclockwise, the bias pulls toward a specific clockwise-oriented grasp.

The two biases do not always pull with the same strength. For example, the anticipatory bias may be weighted more strongly if the intended movement is more difficult and requires more accurate positioning than when it can be easily implemented. The weight of the anticipatory bias may also be stronger for larger rotations than for smaller ones. In the simple case with just the anticipatory bias and the default bias, the model can be expressed as

$$p_{initial} = \frac{w_{anti} p_{anti} + w_{default} p_{default}}{w_{anti} + w_{default}} \quad (1)$$

where $p_{initial}$ is the initial grasp orientation, w_{anti} and $w_{default}$ are the weights of the anticipatory and the default postural bias, respectively, p_{anti} is the anticipatory postural bias, which is set to $p_{anti,ccw}$ for all counterclockwise rotations and to $p_{anti,cw}$ for all clockwise rotations, and $p_{default}$ is the default postural bias. Assuming that the default postural bias contributes with a constant strength and that the anticipatory bias is weighted by the extent of the dial rotation, the characteristic relationship between initial grasp orientations and intended object rotations can be reproduced. Figure 3 shows the predictions under different parameter settings of the model. The different curves show that the model can account for discontinuous and asymmetrical initial grasp orientation patterns, as were reported in Section 2.

Additionally, other biases from other sources could affect initial grasp orientations. For example, Herbort and Butz (2012) showed that arm posture before the onset of the reach or the visual stimulus that instructed a rotation affected initial grasp orientations. Moreover, these biases were stronger for shorter rotations than for larger ones. To account for these findings, additional posture biases may be included in the equation. One interesting facet of the model is that the weight of the anticipatory posture bias is not constant for all possible rotations but depends on the difficulty of the movement (e.g., its extent). The bigger the rotation, the greater the relative weight of the anticipatory posture bias compared to other biases and consequently, the weaker the effect of these other biases on initial grasp orientations. This enables the model to account for the modulation of initial grasp orientation by the extent of the intended rotation (Herbort & Butz, 2012).

4.2 Modeling the Precision Effect and the Hysteresis Effect

The WIMB model also accounts for other modulators of the end-state comfort effect that have been reported in discrete grasp selection tasks. The most prominent modulators are precision requirements and previous grasp selections. Initial grasp orientation in one trial has been found to affect initial grasp orientations in subsequent trials (e.g. Kelso, 1994; Rosenbaum & Jorgensen, 1992). This is called the hysteresis effect. The hysteresis effect is usually studied by giving different object manipulation instructions in a specific order; for example, moving from clockwise rotations to counterclockwise rotations or vice versa. To account for this effect, the WIMB model treats the previously selected posture as just another bias:

$$p_{initial} = \frac{w_{anti}p_{anti} + w_{default}p_{default} + w_{hysteresis}p_{previous}}{w_{anti} + w_{default} + w_{hysteresis}} \qquad (2)$$

where $w_{hysteresis}$ is the weight of the bias imposed by the previous grasp orientation and $p_{previous}$ is the previous grasp orientation. Figure 4 shows a simulation of the hysteresis effect. A sequence of target rotation instructions was presented to the model, going either from -180° to 180° or from 180° to -180° in 45° steps. The first initial grasp orientation in each trial sequence was computed according to Equation (1). Subsequent initial grasp orientations were computed according to Equation (2), in which $p_{previous}$ was set to the initial grasp orientation selected for the previous trial. Figure 4 shows that initial grasp orientations depend on the order of target presentation, according to the hysteresis effect.

Another observation is that the higher the precision requirements at the end of a movement, the greater the alignment of the initial grasp orientation to the intended object manipulation (Rosenbaum et al., 1996; Short & Cauraugh, 1999). This finding can also be accommodated by the WIMB model. To simulate the effect of precision requirements, the weight w_{anti} in Equation (1) was set to the difficulty of the movement, which was defined as the product of rotation extent and an arbitrary coefficient reflecting the precision requirements. Figure 4 shows the simulation results. The higher the precision requirements at the end of the task, the more strongly initial grasp orientations are aligned with the intended manipulation.

4.3 Evaluation and Conclusion

The WIMB model has several attractive features when compared to the optimal planning model. First, it is simpler than the optimal planning model because it does not require a computationally expensive mechanism to generate movements. Second, unlike the optimal planning model, WIMB neither requires precise information about the kinematics of the object manipulation movement nor an anticipation of the costs associated with different end-states. The WIMB model generates grasp postures from information that is either intrinsic to the participant (e.g., the default posture bias) or that is directly available in the form of perceptual variables or current intentions (e.g., the direction and extent of the rotation as explicitly requested in the instructions).

The WIMB model was developed to account for data from continuous tasks. However, the model could also be applied to discrete grasp selection tasks by adding a response rule, which selects one of the discrete choices (e.g. overhand vs. underhand grip) from the actually preferred initial grasp orientations. For example, that grasp orientation could be selected that matches the unconstrained preferred grasp orientation (as generated by the WIMB model) most closely. However, other response rules are also conceivable and different alternatives need to be tested against empirical data in future research.

Even though the WIMB model seems to explain the data better and more economically than the optimal planning model, the WIMB model and the optimal control framework as such are not mutually exclusive. First, the WIMB model explains how human beings plan initial grasp orientations which happen to avoid extreme postures at the end of the movement. From this perspective, the WIMB model is compatible with the notion that humans might generally strive to maximize end-state comfort, but can only roughly approximate this criterion by relying on a rather heuristic strategy for selecting grasp orientations. Second, the WIMB model has several free parameters, such as the default posture bias or the anticipatory posture biases. These parameters could be adjusted based on a cost function. For example, if a person finds himself frequently in awkward postures after manipulating objects he might increase his anticipatory posture biases in order to perform better in the future (cf. van Swieten et al., 2010). Thus, a specific cost function could determines how the parameters and biases proposed in the model are adjusted during learning. Third, if a situation demands a novel criterion for grasp selection, the output of the WIMB-Model might not be directly applicable—but might still be used to bootstrap the planning for an appropriate grasp selection.

In sum, the WIMB model accounts for a broad range of findings and is both more parsimonious and more accurate than the optimal planning account. The WIMB model and the optimal control framework are not actually mutually exclusive. However, the limits of human anticipation and processing have to be kept in mind when optimal control models are evaluated. A normative optimality criterion, such as end-state comfort, may in fact be approximated by rather simple heuristic mechanisms in the human central nervous system.

5 Conclusions

The previous sections have reviewed theories and empirical findings on planning for object manipulation. In the experiments reviewed here, one aspect of the planning process was selecting a suitable grasp to enable carrying out the intended object manipulation adequately. Grasp selection has previously been explained by the optimal planning model, which uses the anticipated end-state of the movement to select the best grasp. However, recent data from continuous grasp orientation selection tasks were incommensurate with this interpretation. In contrast, many findings related to the selection of an initial grasp orientation can be explained and quantitatively modeled with the WIMB model (Herbort & Butz, 2012), which generates an initial grasp orientation through a simple integration of different (heuristic) biases.

The WIMB model's ability to account for a range of phenomena in grasp orientation selection for object manipulation has several major implications. First, with regard to motor planning, it shows that the end-state comfort effect may be explained without assuming that the end-state of a movement is being represented or evaluated when the entire movement sequence is planned. Second, even though representing the effects of individual actions is a prerequisite for action execution (Greenwald, 1970; Hoffmann et al., 1993; Kunde et al., 2004; Prinz, 1997), longer and frequently executed sequences of actions may be planned successfully without explicitly representing the ultimate goal state. Third, simple motor plans such as object manipulations do not necessarily result from an optimal planning process but can rely quite successfully on heuristic action selection patterns. This is yet another feature that the planning of sequential motor actions shares with cognitive decision making.

References

Aflalo, T. N., & Graziano, M. S. A. (2006). Partial tuning of motor cortex neurons to final posture in a free-moving paradigm. *Proceedings of the National Academy of Science 8*, 2909-2914.

Berthier, N. E., Rosenstein, M. T., & Barto, A. G. (2005). Approximate optimal control as a model for motor learning. *Psychological Review, 112*(2), 329-346.

Butz, M. V., Herbort, O., & Hoffmann, J. (2007). Exploiting redundancy for flexible behavior: Unsupervised learning in a modular sensorimotor control architecture. *Psychological Review, 114*(4), 1015-1046.

Cohen, R. G., & Rosenbaum, D. A. (2004). Where grasps are made reveals how grasps are planned: Generation and recall of motor plans. *Experimental Brain Research, 157*, 486-495.

Cowie, D., Smith, L., & Braddick, O. (2010). The development of locomotor planning for end-state comfort. *Perception, 39*(5), 661-670.

Creem, S. H., & Proffitt, D. R. (2001). Grasping objects by their handles: A necessary Interaction between cognition and action. *Journal of Experimental Psychology: Human Perception & Performance, 27*(1), 218-228.

Cruse, H. (2003). The evolution of cognition—A hypothesis. *Cognitive Science, 27*, 135-155.

Cruse, H., Brüwer, M., & Dean, J. (1993). Control of three- and four-joint arm movement: Strategies for a manipulator with redundant degrees of freedom. *Journal of Motor Behavior, 25*(3), 131-139.

Engel, K., Flanders, M., & Soechting, J. (1997). Anticipatory and sequential motor control in piano playing. *Experimental Brain Research, 113*(2), 189-199.

Engelbrecht, S. E. (2001). Minimum principles in motor control. *Journal of Mathematical Psychology, 45*, 497-542.

Fischer, M. H., Rosenbaum, D. A., & Vaughan, J. (1997). Speed and sequential effects in reaching. *Journal of Experimental Psychology: Human Perception and Performance, 23*(2), 404-428.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *The Journal of Neuroscience, 5*(7), 1688-1703.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*(2), 593-609.

Gentilucci, M., Negrotti, A., & Gangitano, M. (1997). Planning an action. *Experimental Brain Research, 115*, 116-128.

Gonzalez, D. A., Studenka, B. E., Glazebrook, C. M., & Lyons, J. L. (2011). Extending end-state comfort effect: Do we consider the beginning state comfort of another? *Acta Psychologica, 136*(3), 347-353.

Grafton, S. T. (2010). The cognitive neuroscience of prehension: Recent developments. *Experimental Brain Research, 204*, 475-491.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77*(2), 73-99.

Haggard, P. (1998). Planning of action sequences. *Acta Psychologica, 99*(2), 201-215.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature,* 394, 780-784.

Herbort, O. (2012). Where to grasp a tool? Task-dependent adjustments of tool transformations by tool users. *Zeitschrift für Psychologie, 220*(1)37-43.

Herbort, O., & Butz, M. V. (2007). Encoding complete body models enables task dependent optimal control. *Proceedings of the International Joint Conference on Neural Networks, 20*, 1639-1644.

Herbort, O., & Butz, M. V. (2009). Anticipatory planning of sequential hand and finger movements. *Journal of Motor Behavior, 41*(6), 561-569.

Herbort, O., & Butz, M. V. (2010). Planning and control of hand orientation in grasping movements. *Experimental Brain Research, 202*(4), 867-878.

Herbort, O., & Butz, M. V. (2011). Habitual and goal-directed factors in (everyday) object handling. *Experimental Brain Research, 213*(4), 371-382.

Herbort, O., & Butz, M. V. (2012). The continuous end-state comfort effect: Weighted integration of multiple biases. *Psychological Research, 76*(3), 345-363.

Herbort, O., Butz, M. V., & Hoffmann, J. (2005). Towards an Adaptive Hierarchical Anticipatory Behavioral Control System. In Castelfranchi, C., Balkenius, C., Butz, M. V., & Ortony, A. (eds.) *From Reactive to Anticipatory Cognitive Embodied Systems: Papers from the AAAI Fall Symposium* (pp. 83-90). Menlo Park, CA: AAAI Press.

Herbort, O., Koning, A., van Uem, J., & Meulenbroek, R. G. J. (2012). The end-state comfort effect facilitates joint action. *Acta Psychologica, 139*(3), 404-416.

Hirayama, M., Kawoto, M., & Jordan, M. I. (1993). The cascade neural network model and a speed-accuracy trade-off of arm movement. *Journal of Motor Behavior, 25*(3), 162-174.

Hoffmann J. (1993). *Vorhersage und Erkenntnis: Die Funktion von Antizipationen in der menschlichen Verhaltenssteuerung und Wahrnehmung* [*Anticipation and cognition: The function of anticipations in human behavioral control and perception*]. Göttingen: Hogrefe.

Hughes, C. (1996). Brief report: Planning problems in autism at the level of motor control. *Journal of Autism and Developmental Disorders, 26*(1), 99-107.

Janssen, L., Crajé, C., Weigelt, M., & Steenbergen, B. (2010). Motor planning in bimanual object manipulation: Two plans for two hands? *Motor Control, 14*(2), 240-254.

Johnson, S. H. (2000). Thinking ahead: The case for motor imagery in prospective judgements of prehension. *Cognition, 74*(1), 33-70.

Kelso, J. A. S., Buchanan, J. J., & Murata, T. (1994). Multifunctionality and switching in the coordination dynamics of reaching and grasping. *Human Movement Science 13*(1), 63-94.

Klein-Breteler, M. D., Hondzinski, J. M., & Flanders, M. (2003). Drawing sequences of segments in 3D: Kinetic influences on arm configuration. *Journal of Neurophysiology 89*, 3253-3263.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology. Section A: Human Experimental Psychology, 57*, 87-106.

Marteniuk, R. G., Mackenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology 41*(3), 365-378.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology, 35*, 0191-1101.

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2006). Anticipatory planning deficits and task context effects in hemiparetic cerebral palsy. *Experimental Brain Research, 172*(2), 151-162.

Novak, K., Miller, L., & Houk, J. (2000). Kinematic properties of rapid hand movements in a knob turning task. *Experimental Brain Research, 132*(4), 419-433.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology 9*(2), 129-154.

Robert, T., Beurier, G., & Wang, X. (2009). Arm postural anticipation for rotating a spherical object. *Computer Methods in Biomechanics and Biomedical Engineering 12*(1), 217-218.

Rosenbaum, D. A., & Jorgensen, M. J. (1992). Planning macroscopic aspects of manual control. *Human Movement Science, 11*(1-2), 61-69.

Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G. J., Vaughan, J., & Engelbrecht, S. E (1995). Planning reaches by evaluating stored postures. *Psychological Review, 102* (1), 28-67

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Siotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and Performance, Vol. XIII* (pp. 321-345). Lawrence Erlbaum Associates.

Rosenbaum, D. A., Meulenbroek, R. G. J., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: applications to grasping. *Psychological Review, 108*(4), 709-734.

Rosenbaum, D. A., Slotta, J. D., Vaughan, J., & Plamondon, R. (1991). Optimal movement selection. *Psychological Science, 2*(2), 86-91.

Rosenbaum, D. A., van Heugten, C. M., & Caldwell, G. E. (1996). From cognition to biomechanics and back: The end-state comfort effect and the middle-is-faster effect. *Acta Psychologica, 94*, 59-85.

Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992). Time course of movement planning: Selection of handgrips for object manipulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(5), 1058-1073.

Sabes, P. N. (2000). The planning and control of reaching movements. *Current Opinion in Neurobiology, 10*(6), 740-746.

Schütz, C., Weigelt, M., Odekerken, D., Klein-Soetebier, & Schack, T. (2011). Motor control strategies in a continuous task space. *Motor Control, 15(3), 321-341.*

Short, M. W., Cauraugh, J. H. (1997). Planning macroscopic aspects of manual control: end-state comfort and point-of-change effects. *Acta Psychologica, 96*(1-2), 133-147.

Short, M. W., & Cauraugh, J. H. (1999). Precision hypothesis and the end-state comfort effect. *Acta Psychologica, 100*(3), 243-252.

Thibaut, J.-P., & Toussaint, L. (2010). Developing motor planning over ages. *Journal of Experimental Child Psychology, 105*(1-2), 116-129.

Todorov, E. (2004). Optimality principles in sensorimotor control. *Nature Reviews Neuroscience, 7*(9), 907-915.

Todorov, E., & Jordan, M. I. (2002). Optimal feedback control as a theory of motor coordination. *Nature Neuroscience, 5*(11), 1226-1235.

Uno, Y., Kawato, M., & Suzuki, R. (1989). Formation and control of optimal trajectory in human multijoint arm movement: Minimum torque-change model. *Biological Cybernetics, 61*(2), 89-101.

van der Vaart, A. J. M. (1995). Arm movements in operating rotary control (Doctoral thesis, Technische Universiteit Delft, Delft, The Netherlands). Retrieved from http://repository.tudelft.nl/assets/uuid:20033739-71d9-42a4-bc3e-058d78ab8cec/ide_vaart_19950616.PDF

van Swieten, L. M., van Bergen, E., Williams, J. H., Wilson, A. D., Plumb, M. S., Kent, S. W., & Mon-Williams, M. A. (2010). A test of motor (not executive) planning in developmental coordination disorder and autism. *Journal of Experimental Psychology: Human Perception & Performance, 36*(2), 493-499.

Weigelt, M., Kunde, W.,& Prinz, W. (2006). End-state comfort in bimanual object manipulation. *Experimental Psychology, 53*(2), 143-148.

Weigelt, M., Rosenbaum, D. A., Huelshorst, S., & Schack, T. (2009). Moving and memorizing: Motor planning modulates the recency effect in serial and free recall. *Acta Psychologica, 132*(1), 68-79.

Weiss, D. J., Wark, J. D., & Rosenbaum, D. A. (2007). Monkey see, monkey plan, monkey do: The end-state comfort effect in cotton-top tamarins (*Saguinus oedipus*). *Psychological Science, 18*(12), 1063-1068.

Wolpert, D. M., Doya, K., & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society of London, 358*, 593-602.

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks, 11*(7-8), 1317-1329.

Zhang, W., & Rosenbaum, D. A. (2008). Planning for manual positioning: The end-state comfort effect for manual abduction-adduction. *Experimental Brain Research, 184*, 383-389.

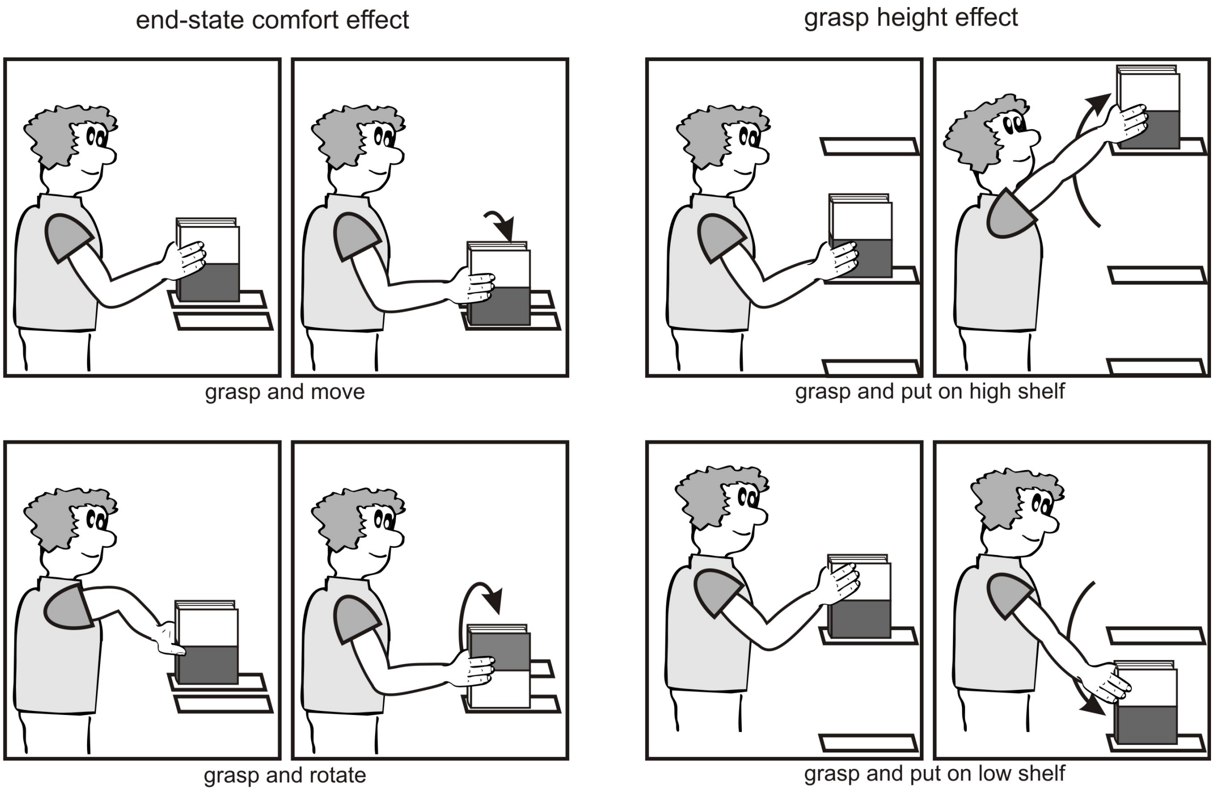

Figure 1. Two examples of anticipatory planning. The cartoon shows two examples of anticipatory planning. The “end-state comfort effect” refers to the finding that grasp orientations are selected based on forthcoming object rotations (Rosenbaum et al., 1990). The “grasp height effect” refers to the selection of different grasp points depending on the intended object displacement (Cohen and Rosenbaum, 2004).

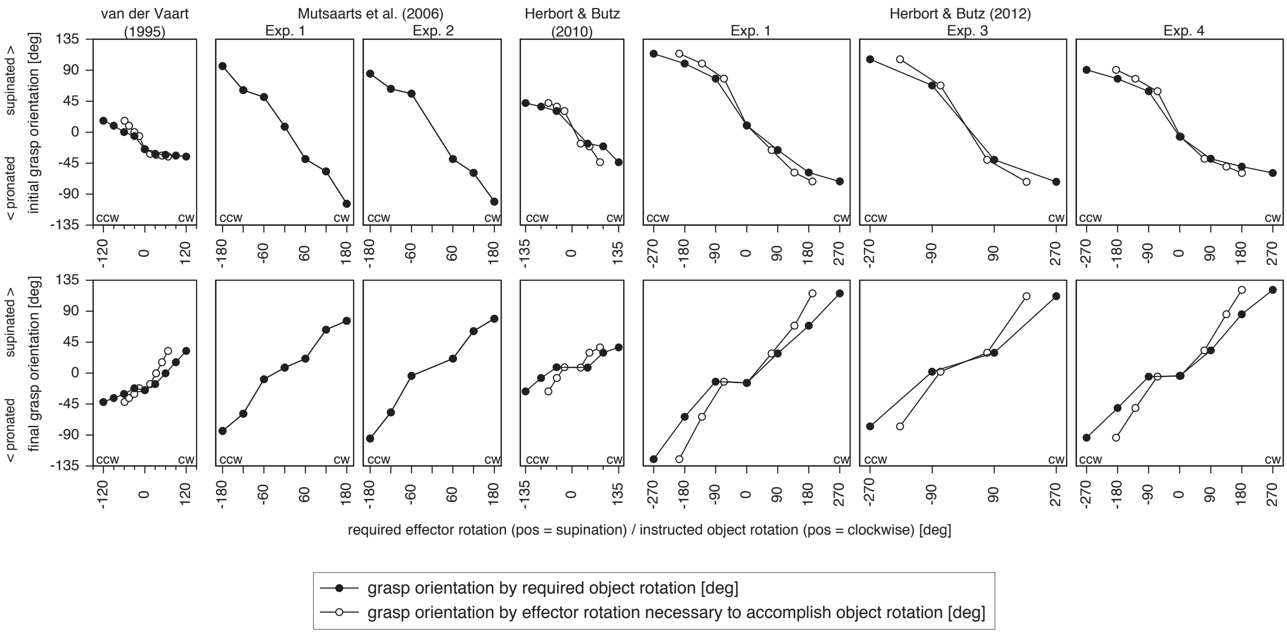

Figure 2. Grasp Orientations. The charts show the initial grasp orientation (top row) and final grasp orientation (bottom row) reported in different experiments for different intended rotation angles (positive values denote supinations, for the sake of comparability, and positive rotation angles denote clockwise turns). Grasp orientations are plotted by the object rotation actually required and by the rotation of the recorded effector (e.g., of the forearm) necessary to accomplish the required object rotation (except for the experiments of Mutsaarts et al.).

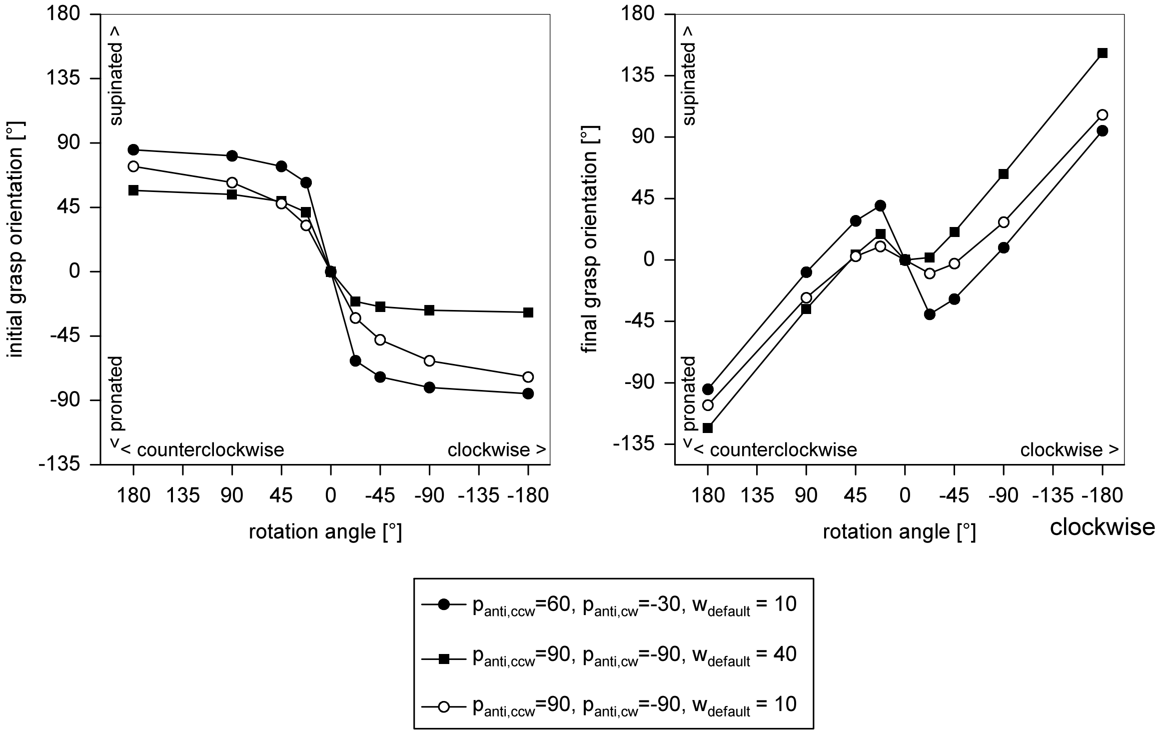

Figure 3. Predictions of the WIMB-model. The chart shows the relationship between initial / final grasp orientation and intended rotation angle (positive rotation angles denote counterclockwise turns, positive grasp orientations denote supinations) for different parameter settings of the WIMB model as formulated in Equation 1. In all cases, $p_{default}$ was set to 0. The parameter p_{anti} of Equation 1 was set to $p_{anti,ccw}$ for counterclockwise rotations and $p_{anti,cw}$ for clockwise rotations.

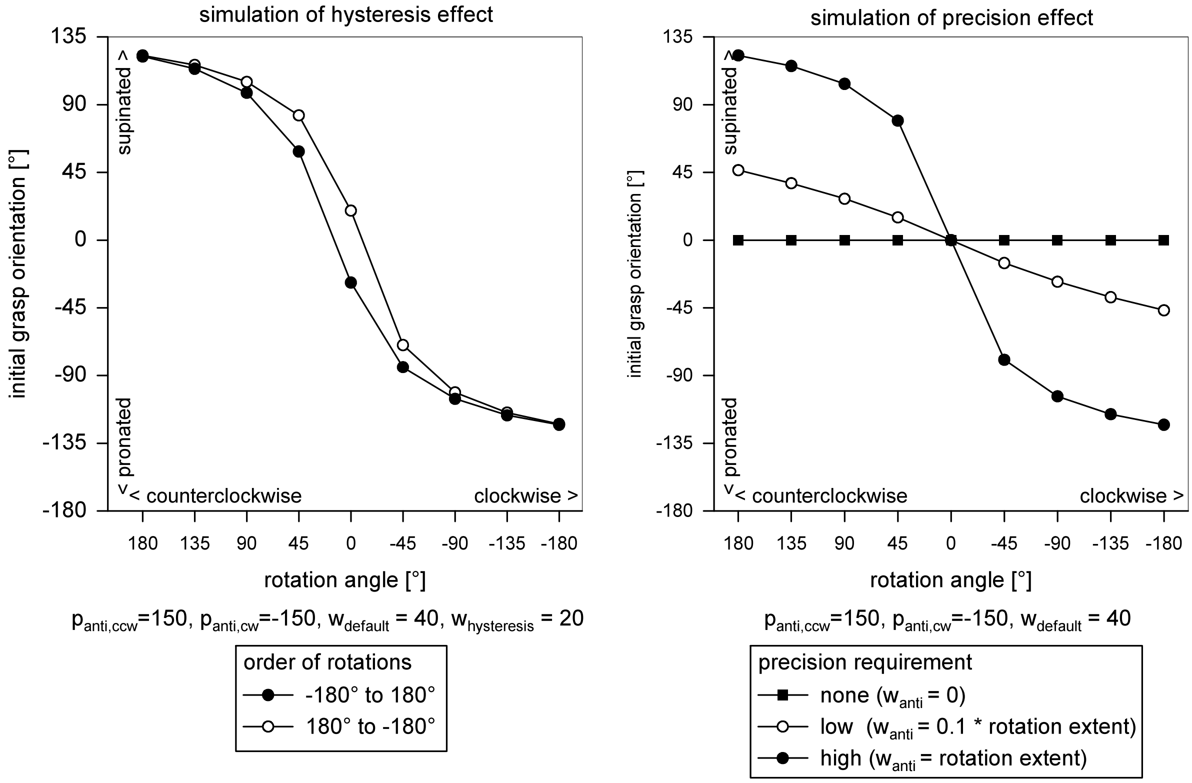

Figure 4. Simulation of the hysteresis and precision effect with the WIMB-model. The charts shows simulations of the hysteresis effect (left) and precision effect (right) on initial grasp orientations (positive rotation angles denote counterclockwise turns, positive grasp orientations denote supinations). In all cases, $p_{default}$ was set to 0.

Table 1: Summary of the studies included in the review

Reference	Rotation object	Sample size	Data source in original publication	Recorded variables	Remarks
van der Vaart (1995)	circular knob	n = 13	Fig 5.1	forearm supination	
Mutsaarts et al. (2006) Experiment 1	hexagonal knob	n = 11	Fig 3	finger placement	only data from healthy controls
Mutsaarts et al. (2006) Experiment 2	hexagonal knob	n= 5	Table 3	finger placement	only data from healthy controls
Herbort et al. (2010)	circular knob	n = 38	original data	forearm supination	data averaged over other conditions
Herbort et al. (2012) Experiment 1	box with circular handle	n = 10	original data	forearm supination	
Herbort et al. (2012) Experiment 3	box with circular handle	n = 15	original data	forearm supination	data averaged over other conditions
Herbort et al. (2012) Experiment 4	box with circular handle	n = 15	original data	forearm supination	data averaged over other conditions