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Optimal control in the critical phase of movement: A functional approach to motor planning processes

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A B S T R A C T

Grasping movements are often planned in a way that they end in a position where joints are in an anatomically medial position. This behaviour is termed the "end-state comfort" (ESC) effect (Rosenbaum et al., 1990). We suggest that the anatomically medial position is favoured to control the most difficult part of the movement. In most experiments investigating ESC, objects have to be placed onto a target location, and the highest precision demand occurs at the end of the movement. Thus, ESC is confounded with movement difficulty. In this study, we dissociate movement difficulty and ESC. In our experiments, participants had to execute a task where the critical part of the movement was either at the end or at the beginning of the movement. Participants' grasping behaviour confirmed the hypothesis that movement planning is constrained by a goal for optimal control during the part of the movement that demands the highest precision, rather than by a goal to end in a comfortable state (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). We identified recall and movement plan generating processes of motor planning (Cohen & Rosenbaum, 2004), that ensure the optimal control in the critical part of movement. Our results indicate that recall processes depend on motor experience which is acquired in different time scales. We suggest that motor planning processes are triggered only if the costs for executing movements controlled by recall processes exceed the costs for generating a motor plan.

1. Introduction

Frequently, when people pick up an object, they adjust their grasp in different ways, which depend on how they intend to use the object. The planning of the initial grasping position reflects subsequent movement goals (Cohen & Rosenbaum, 2004, 2011) or the goals of others (Gonzalez, Studenka, Glazebrook, & Lyons, 2011). There are a number of studies that show that adults tend to select a grasping orientation that leads to a comfortable final posture, where joints are in an anatomically medial position, even if reaching a comfortable final posture requires adopting an awkward posture initially (Rosenbaum et al., 2012). In a seminal experiment (Rosenbaum et al., 1990), right-handed participants were asked to grasp a horizontally orientated bar, which was lying on a pair of cradles, to turn the bar 90° and to place it on a target on its left or right end in an upright position. In this experiment, all participants picked the bar up with an overhand grip when it was supposed to be placed on its right end and with an underhand grip when it was supposed to be placed on its left end. The observed difference reflects the fact that both types of grips allow a thumb-up position of the hand at the target position and ensure a comfortable end state. The preference for final comfort over initial comfort was termed the end-state comfort (ESC) effect (Rosenbaum et al., 1990). In further experiments, researchers showed that the ESC is also found with increasing age in children (Thibaut & Toussaint, 2010; van Swieten et al., 2010; Weigelt & Schack, 2010) and even in nonhuman animals (Chapman, Weiss, & Rosenbaum, 2010; Weiss, Wark, & Rosenbaum, 2007). The basic experimental paradigms used to study this effect included the grasping and turning of objects such as knobs (Rosenbaum, Cohen, Meulenbroek & Vaughan, 2006), bars (Weigelt, Kunde, & Prinz, 2006; Weigelt & Schack, 2010), or glasses (Adalbjornsson, Fischman, & Rudisill, 2008), and the picking up and placing of objects such as plungers on top of a table or shelves of varying heights (Cohen & Rosenbaum, 2011; van der Wel & Rosenbaum, 2010; Weigelt, Cohen, & Rosenbaum, 2007).

It could be demonstrated that in addition to goal posture, motor planning is influenced by previous experience in the motor task. For instance, in a series of tasks, participants tended to use the same type of grip that they used previously, even if changes in the task led to a less comfortable end-state (Cohen & Rosenbaum, 2004, 2011; Rosenbaum, van Heugten, & Caldwell, 1996; Short & Cauraugh, 1999). Thus, there seems to be a trade-off between the cognitive costs of motor planning that are required to change the successful grip position and the experienced physical costs caused by an awkward end state (Cohen & Rosenbaum, 2011; Weigelt, Rosenbaum, Huelshorst, & Schack, 2009).

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Rosenbaum, Barnes, Vaughan, and Jorgensen (1992) detected a third factor that influences grasping movements, which they called the thumb-toward bias. In one experiment, these authors found that participants tended to grip a bar with the thumb and index finger directed towards a pointer that was marked on one end of the bar. Rosenbaum et al. (1992) argued that attentional constraints might explain the thumb-toward bias because the thumb and index finger are more associated with attention processes than the little finger. In their experimental design, participants had to pay more attention to the pointer, and therefore, they grabbed the pointer with the region of the hand that is more associated with attention. Herbort and Butz (2011) suggest an alternative interpretation: The bias towards a specific grip position might be due to a "habitual system" that controls the grip in a way in which people habitually grasp for specific objects. In this paper, we call those control processes the "habitual mode". This leaves the question open if the involved control processes are executed by a distinct system or by a different working mode of the same system.

To summarise, three processes were reported that influence the planning of the grip position in pick-up-and-put-down movements: 1) cognitive-motor planning processes, which take into account the movement goal and are demonstrated by the ESC effect; 2) recall processes, which are influenced by the experience of preceding movements on a short time scale and are demonstrated for instance by a hysteresis effect; and 3) recall processes on a long time scale depending on acquired habits, which are task specific and may be demonstrated by a dominance of a specific initial grip position.

In the described experiments we focus on the investigation of the functional foundation of planning processes. We assume that it is not the end-state comfort that constrains motor planning. Instead, we propose a criterion we call optimal control in the critical phase (OCICP). Short and Cauraugh (1999) demonstrated that a comfortable position assures an optimal control. The OCICP-hypothesis suggests that movements are planned in a way that the comfortable state is used in the critical phase, which is the phase in the movement where the highest precision is needed.

There are two implications of this hypothesis. First, it could be that there is no "critical phase" within the movement sequence. This might be the case when all parts of the sequence require an equal amount of precision, or if there is no notable precision demand at all. In these cases other planning processes than OCICP will determine the grip position. Second, if there is a critical phase in the movement sequence, some experience with the actual task is necessary to obey the OCICP because the critical phase within the movement sequence must be correctly estimated. This correct estimate can already be acquired by previous experiences with similar tasks; it could also develop in the course of executing a specific task.

But why should motor planning rely on the OCICP instead of the ESC effect? Until recently (Rosenbaum et al., 2012), the question concerning the functional advantage of ESC was not raised. We define a functional advantage as a feature that supports the successful achievement of the movement's goal. A functional advantage is likely to be considered when planning processes take place. The favoured explanation for the ESC effect is the precision hypothesis (Rosenbaum et al., 1996). This hypothesis states that a comfortable position allows for greater precision than an uncomfortable position (Short & Cauraugh, 1999). Rosenbaum et al. (1996) and Rosenbaum, Cohen, et al. (2006) observed that if low precision is required at the end of a movement, the ESC effect is observed in fewer participants or is not obtained at all. The results of Short and Cauraugh (1999)) confirmed these findings. In a recent review, Rosenbaum et al. (2012) assumed that it might be a goal for optimal control rather than greater comfort that causes the ESC effect, and we aim to strengthen this assumption. Specifically, we suggest that it is not the end-state but the part of the highest precision demand which we call "critical part" that constrains action planning. In pick-up-and-put-down tasks (the usual paradigm for investigating the ESC), the "put down" part of the action arguably needs more precision than the "pick-up" part. Thus, in these experiments, the end-state and critical part coincide. This confound implies that it is not possible to discern whether motor planning processes are constrained by achieving ESC or by achieving an OCICP of a movement. For this reason, in our experiment, we manipulated the appearance of the critical part. We hypothesised that participants would show a comfortable position, one that allows for optimal control, in the part of the movement that requires the highest degree of precision.

2. Experiment 1

2.1. Method

Seventy-two right-handed students from the University of Augsburg were randomly selected (19 male, 53 female; average age = 22.6 years, SD = 4.6 years). Participants participated voluntarily and received no compensation. All participants were naïve to the experiment. Written informed consent was obtained from all participants.

The task was to pick up, turn, and drop a baton. As part of this movement, the baton had to be fed through the elliptical holes of two obstacles. The participants had to reach through the hole of the first obstacle, pick up the baton and then feed it through the hole of the first obstacle. On the way from the first to the second obstacle, they had to turn the baton 180° on the frontal plane and then fit the baton through the hole of the second obstacle. The elliptical form of the hole was chosen to enforce that the baton could only be fed through the hole in an upright position. The obstacles had holes of different sizes: large, medium, and small (see Fig. 1). Participants could use only their right hand and were not allowed to change their grip in any part of the movement sequence. They were instructed not to touch the obstacles with the bar or with their hand and to execute the movement at a speed that they felt was comfortable. Participants had to execute the task in three blocks, each of which included three different conditions. In one block, the hole in the first obstacle was always smaller than the one in the second obstacle. The possible conditions in this block were Small → Large (i.e., the small hole obstacle was followed by the large hole obstacle), Small → Medium, and Medium → Large. In another block, this sequence was reversed and the conditions were Large → Medium, Large → Small and Medium → Small. In a third block, the holes of each obstacle were of equal size and the conditions were Large → Large, Medium → Medium, and Small → Small. The order of the blocks, as well as the order of the conditions within the blocks, was permuted across all participants. In between conditions, participants were asked to turn their back to the obstacles while the experimenter changed the obstacles; thus, participants did not observe the process of changing the obstacles. Each of the 36 possible permutations of order of blocks and conditions was completed by two participants. One participant had the first obstacle on the right-hand side and had to execute the movement from right to left; the other participant had the first obstacle on the left-hand side and had to execute the movement from left to right. To compensate for body height differences between participants, the obstacles were placed on top of any number of wooden plates, ranging from zero to four, which allowed participants to use an elbow angle that was most comfortable for them. Participants were videotaped as they executed the instructed movements. The video tapes were evaluated to obtain the movement times for the three different movement sections: The movement time from the initial grasp to passing obstacle 1 (t1), from passing obstacle 1 to passing obstacle 2 (t2), from passing obstacle 2 to the release of the baton (t3). t1 should be influenced by the hole size of obstacle 1, and t2 by the hole size of obstacle 2; smaller holes should lead to longer movement times. This prediction was tested separately for the 1st and the 2nd obstacle by one-way ANOVAs with a three-level within subject factor hole size (Large, Medium, Small). Dependent measure was the mean t1 for the three conditions with equal hole sizes of the first

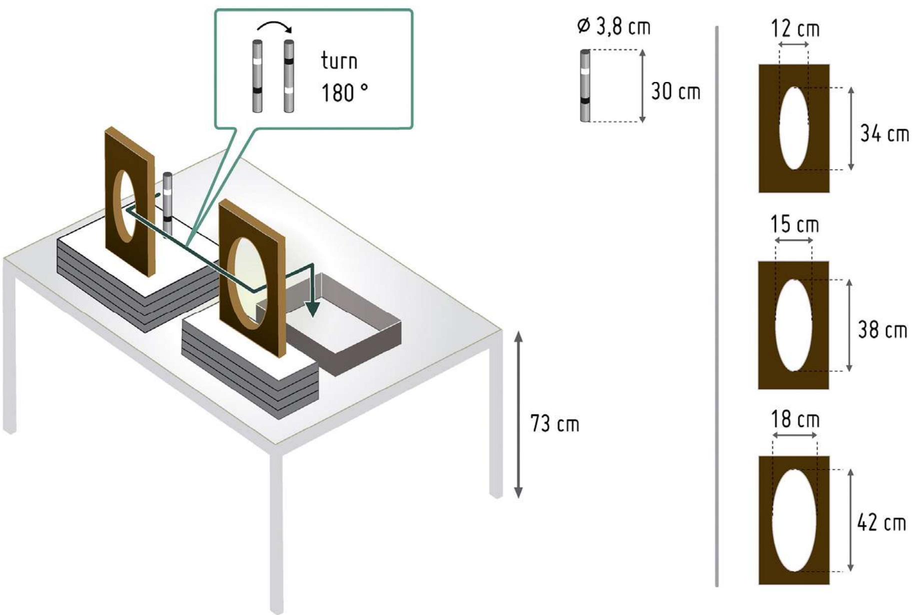

Fig. 1. Set-up of experiment 1. Participants stand in front of the long side of the table and grab the baton by putting their hand through the hole of the obstacle.

obstacle or the mean t2 for the three conditions with equal hole sizes of the second obstacle respectively. Greenhouse-Geisser correction for the degrees of freedom was applied in cases where Mauchly's test of sphericity was significant. The critical part of the movement was defined by the point at which participants passed the baton through the obstacle with the small hole, the end state was the state of the hand and forearm when letting the baton drop into the box.

We hypothesised that participants would follow the OCICP control strategy and would use an initial grip position that allowed for a comfortable thumb-up position (as opposed to an uncomfortable thumb-down position) when they fed the baton through the obstacle with a small hole. To analyse the significance and the effect sizes of the mean differences between the blocks and the movement direction we conducted a two-way ANOVA with a three-level within-subject factor blocks (Equal, Smaller → Larger, Larger → Smaller) and a two level between-subject factor direction (right to left, left to right), dependent variable was the mean percentage of the initial thumb down grip position over the three trials in each block.

2.2. Results

Overall, we analysed 648 trials. In six trials (0.93%) participants touched the obstacle with the baton. Movement times were given in Table 1.

The movement time from grab to obstacle 1 differed significantly depending on hole size in obstacle 1 ($F(1.25;\ 88.65) = 77.65$, $p < .001$, $\eta_p^2 = .522$), post-hoc pairwise comparison revealed significant movement time differences for all three hole sizes of obstacle 1.

Table 1
Mean movement times (in seconds) and standard errors of the mean for the three movement parts of the experimental tasks and for the different obstacle sizes.

		First obstacle			Second obstacle		
		Large	Medium	Small	Large	Medium	Small
Grab to obstacle 1	Mean	.58	.73	1.10	.80	.80	.82
	SE_{mean}	.028	.047	.061	.058	.049	.055
Obstacle 1 to obstacle 2	Mean	1.53	1.51	1.52	1.36	1.39	1.81
	SE_{mean}	.080	.086	.077	.072	.054	.099
Obstacle 2 to release	Mean	.59	.58	.56	.52	.56	.65
	SE_{mean}	.039	.042	.035	.035	.034	.045

The movement time from obstacle 1 to obstacle 2 differed significantly depending on hole size in obstacle 2 ($F(1.33;\ 94.2) = 33.78$, $p < .001$, $\eta_p^2 = .32$). Post-hoc pairwise comparisons showed that movement times for the small hole differ significantly from the movement times for the two other hole sizes.

In 28.1% of all trials, participants started with an initial thumb-down position and ended their movement in the comfortable thumb-up position. There were no significant differences between the three blocks ($F < 1$) (Table 2). 53 participants (73.6%) kept the same grip position throughout all nine conditions. There were no statistically significant differences between the executions of movements from left to right versus from right to left ($F < 1$).

2.3. Discussion

To confirm the end-state-comfort (ESC) hypothesis, participants were expected to start in the thumb-down position and to end in the comfortable thumb-up position throughout all nine trials. To confirm the optimal control in the critical part (OCICP) hypothesis, participants were expected to show the thumb-up position in the critical part, that

Table 2
Percentages of an initial thumb-down grip position under the different conditions. The rows Equal, Smaller–Larger, and Larger–Smaller average the values of the three above presented conditions.

Condition	Percentage
Small → Small	26.4
Medium → Medium	29.2
Large → Large	27.8
Equal	27.8
Small → Medium	27.8
Small → Large	23.6
Medium → Large	29.2
Smaller → Larger	26.8
Medium → Small	27.8
Large → Small	30.6
Large → Medium	30.6
Larger → Smaller	29.6

is, while passing the baton through the smaller hole. This demands an initial thumb-down position in all conditions in which the first obstacle had a larger hole then the second obstacle (Large → Medium, Large → Small, Medium → Small) and an initial thumb-up position in conditions in which the first obstacle had a smaller hole then the second one (Small → Medium, Small → Large, Medium → Large). The OCICP does not make a prediction regarding conditions where movements are made through holes of equal sizes.

The results show that neither the ESC hypothesis nor the OCICP hypothesis could explain the data. The low percentage of movements that were initiated from a thumb-down grip position contradicts the ESC hypothesis, which would predict that participants would start their movement from a thumb-down position in order to end in a comfortable thumb-up position. A possible explanation for the observed data is that the tasks employed in experiment 1 had low precision demands, and because of this low demands, participants did not have to engage in cognitive-motor planning regarding the initial grip position. This result was first found by Rosenbaum et al. (1996) in tasks where no precision is needed. We assume that instead of planning the grasp in advance, participants rather control the initial grasp in the habitual mode. So, the absence of notable precision demands may have caused participants not to notice or require a critical phase in the movement sequence. Thus, participants avoided the cognitive costs involved with a generation of a new motor plan and did not change their grip position. Furthermore, participants may have been unable to take into account their experience of the preceding trial because conditions varied on a trial-by-trial basis.

Based on these observations, we raised the precision demand of the critical task of experiment 2. Additionally, to enable participants to reflect on their previous motor experience, the task in experiment 2 contained blocks of 5 consecutive trials of the same condition.

3. Experiment 2

3.1. Methods

Ninety-six right-hand dominant students attending the University of Augsburg (44 male, 52 female; average age = 23.1 years, *SD* = 4.3 years) volunteered to participate. They received no compensation, and all participants were naïve to the experiment and the concepts being tested. Written informed consent was obtained from all participants. The participants' task was essentially the same as it was in experiment 1. However, instead of having to handle a baton, participants had to pick up, turn and drop a small shield, which was made of a baton and an elliptical card board (d_1 = 30 cm, d_2 = 10 cm) that was mounted onto the baton. In experiment 2, we did not use an obstacle with a medium sized hole and instead used only the obstacles with large and small sized holes. As shown in experiment 1, the direction of the movement did not influence the grasping behaviour, so we did not include the right to left direction from experiment 1; instead, the first obstacle was always on the left-hand side and the second obstacle always right to it. Participants were instructed to reach through the first obstacle, grab the shield by the baton, feed the shield through the hole of the first obstacle, turn the shield 180° in the frontal plane, feed it through the second obstacle, and drop the shield into a box (Fig. 2). Participants were instructed to use only their right hand and were not allowed to change their grip at any point during the movement sequence. They were instructed not to touch the obstacles and to execute the movement at a speed that they felt was comfortable. The task had to be executed under three different conditions: (a) the first hole was small and the second hole was large (Small → Large condition); (b) the first hole was large and the second hole was small (Large → Small condition); and (c) both holes were of equal size (Equal condition). In the Equal condition, we used obstacles with large holes for half of the participants and obstacles with small holes for the remaining half of participants. Participants could observe the rearranging of the obstacles.

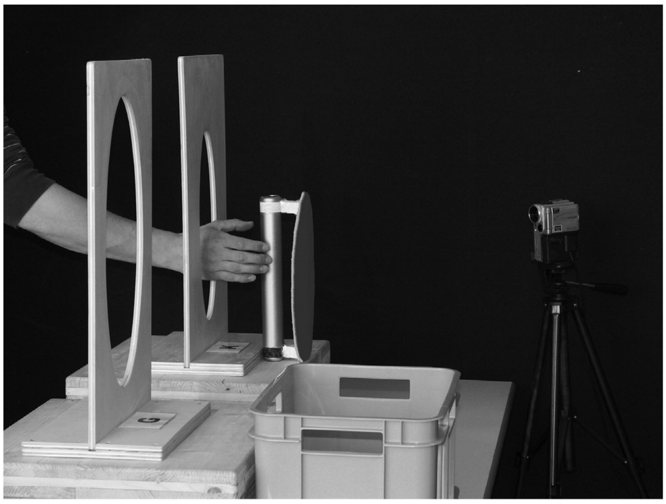

Fig. 2. Set-up of experiment 2. Participants had to grasp the "shield", feed it through the hole of the first obstacle, turn it 180° in the frontal plane, feed it through the second obstacle, and drop it into the box.

In each condition, participants performed five consecutive trials. The order of the conditions was permuted across all participants. Consequently, there were 6 different orders of the conditions, each of which was executed by 16 participants. These condition orders were as follows: 1) Large → Small, Small → Large, Equal; 2) Large → Small, Equal, Small → Large; 3) Equal, Large → Small, Small → Large; 4) Small → Large, Large → Small, Equal; 5) Small → Large, Equal, Large → Small; or 6) Equal, Small → Large, Large → Small.

Participants were videotaped as they executed the movement sequences. The video tapes were evaluated to obtain the movement times for the three different movement sections: The movement time from the initial grasp to passing obstacle 1 (t1), from passing obstacle 1 passing of obstacle 2 (t2), from passing obstacle 2 to the release of the shield (t3). Two participants had to be omitted because of faults in the video tape. Similar to experiment 1, feeding the shield through the small hole should lead to longer movement times than feeding it through the large hole. This prediction was tested separately for the 1st and 2nd obstacles by one-tailed paired-sample *t*-tests. Dependent measures were the mean t1 values for the conditions with the same hole sizes of the first obstacle or the mean t2 values for the conditions with the same hole sizes of the second obstacle respectively.

The critical part of the movement was defined by the point at which participants passed the shield through the obstacle with the small hole. The end state was the state when letting the shield drop into the box.

As in experiment 1, we hypothesised that participants would use an initial grip position that allows for optimal control in the critical part (OCICP) of the movement. According to the OCICP, in the Small→ Large condition, participants should start with a thumb-up position, whereas in the Large→Small condition, they should start with an initial thumb-down position. In contrast to the OCICP framework, the ESC effect would predict that participants would initiate movements from a thumb-down position in all of the conditions.

To analyse the significance and effect sizes of the mean differences between the conditions and the single trials, we conducted a two-way analysis of variance with a three level within-subject factor condition (Large → Small, Equal, Small → Large) and a five level within-subject factor trial (trials 1 to 5). Dependent variable was the mean percentage of initial thumb-down grip positions.

Mean differences between the conditions in the direction of the *a priori* OCICP hypothesis were analysed pairwise using a one-tailed, one-sample *t*-test. The alpha level was set to .05, and effect sizes were calculated using Cohen's *d* (*t*-test) or partial η_p^2 (ANOVA). Greenhouse-

Table 3
Mean movement times (in seconds) and standard errors of the mean (in brackets) for the three movement parts of the experimental tasks and for the experimental conditions.

Condition	Mean movement time (and se_{mean}) in seconds		
	Grab to obstacle 1	Obstacle 1 to obstacle 2	Obstacle 2 to release
Large → Small	1.05 (0.05)	3.29 (1.29)	1.69 (0.08)
Small → Large	3.38 (0.17)	1.70 (0.06)	0.90 (0.03)
Equal (small)	3.36 (0.19)	3.74 (0.26)	1.66 (0.10)
Equal (large)	0.86 (0.04)	1.54 (0.09)	0.90 (0.03)

Geisser correction for the degrees of freedom was applied in cases where Mauchly's test of sphericity was significant.

3.2. Results

Overall, we analysed 96 participants × 3 conditions × 5 trials per condition = 1440 trials. In 27 trials, participants touched an obstacle with the shield. Participants used an initial thumb-up grip position 937 times (65.07%) and an initial thumb down position 503 times (34.93%). Movement times are shown in Table 3.

The movement times from grab to obstacle 1 differ significantly for small or big holes in obstacle 1, t (93) = 15.03, $p < .001$. The movement times from obstacle1 to obstacle 2 differ for small or big holes in obstacle 2, t (93) = 13,63, $p < .001$.

Though there were also significant differences in movement times in the two Equal conditions (Small → Small, Large → Large), no differences could be observed in the initial grip position. 31.25% of those participants who were presented with obstacles with two large holes used an initial thumb-down grip position, compared with 31.67% of those participants who were presented with two small holes. This difference is most likely mere chance. So, in the remainder we treat both Equal conditions as one.

The initial grip position depended on the condition, $F(1.9, 178.3) = 41.3, p < .001, \eta_p^2 = .30$. Means and standard errors of the means in the different conditions are shown in the "overall" row of Table 4. On average, participants used the initial thumb-down position less frequently in the Small → Large condition than in the Equal condition, t (95) = 3.35, $p = .001$, $d = 0.35$, and also less frequently in the Small → Large condition than in the Large → Small condition, t (95) = 8.02, $p < .001$, $d = 0.82$. In the Equal condition, the initial thumb-down position occurred significantly less frequently than in the Large → Small condition, t (95) = 6.06, $p < .001$, $d = 0.62$.

To assess the influence of participants' experience on each preceding trial within the same condition, we analysed interaction effects between participants' initial grip position over different trials and the condition, $F(6.0, 568.8) = 8.45$, $p < .001$, $\eta_p^2 = .08$ (Fig. 3). In the Equal condition, the grip position did not change significantly across trials. In the Large → Small condition, participants developed a preference for the initial thumb-down position over the course of the five trials. In the Small → Large condition, participants' use of an initial thumb-up position tended to increase over the five trials.

As mentioned in the introduction, the initial grip position may be influenced by participants' recall of preceding conditions. To investigate whether this influence took place, we analysed condition order effects. Specifically, we analysed data in the Large → Small condition and the Small → Large condition as a function of which condition was executed before the other. We divided the participants into two subgroups. The subgroup labelled "Large → Small before Small → Large" included all 48 participants who executed the Large → Small condition before the Small → Large condition, whereas the subgroup labelled "Small → Large before Large → Small" did vice versa (Table 4). In the Large → Small condition participants of the "Large → Small before Small → Large" subgroup used the initial thumb-down position in 64.6% of the trials, in the "Small → Large before Large → Small" subgroup just in 40.4% of the trials. In the Small → Large condition, participants of the "Large → Small before Small → Large" subgroup used the initial thumb-down position in 28.75% of the trials, in the "Small → Large before Large → Small" subgroup just in 12.9% of the trials. As the order of the Equal condition was not considered when dividing the participant into subgroups, the differences in Equal condition could not be analysed with respect to the order of conditions. So a separate two-way ANOVA with a two level within subject factor condition (Small → Large and Large → Small) and the two level between subject factor subgroup ("Small → Large before Large → Small" and "Large →Small before Small → Large") was conducted, showing significant main effects between conditions ($F(1;94) = 64.42$, $p < .001$, $\eta_p^2 = .41$) and between subgroups ($F(1;94) = 8.94$, $p = .004$, $\eta_p^2 = .09$), but no significant interaction.

3.3. Discussion

The main focus of experiment 2 is to design a critical experiment to test two hypotheses that make predictions regarding the goal of cognitive-motor planning; these hypotheses are the end state comfort (ESC) hypothesis and the optimal control in critical part of the movement (OCICP) hypothesis. In experiment 2, the ESC predicts a preference for the initial thumb-down grip position, which would lead the participant to end up in a comfortable thumb-up position at the end of the movement, regardless of the obstacle constellation. In contrast, the OCICP hypothesis predicts an initial thumb-down grip position in the Large → Small condition and an initial thumb-up grip position in the Small → Large condition. The crucial condition

Table 4
Mean percentages (and standard error of the mean) of an initial thumb-down position as a function of condition and the order of the presented condition in experiment 2. In each cell, 16 participants were evaluated. A reading example: In the Large → Small condition (middle column), where participants had to first feed the shield through the obstacle with the large hole, then turn it and move it through the small hole, they used in 27.5% (SE: 10.63) of the cases an initial thumb-down grip when this condition was asked for in third place immediately after the Small → Large condition (sequence 6).

Sequence	Condition		
	Equal	Large → Small	Small → Large
1) Large → Small, Small → Large, Equal	51.25 (10.8)	68.75 (7.52)	36.25 (10.2)
2) Large → Small, Equal, Small → Large	63.75 (9.5)	78.75 (6.94)	25.0 (9.75)
3) Equal, Large → Small, Small → Large	30.0 (10.0)	46.25 (11.65)	25.0 (11.2)
Large → Small before Small → Large subgroup	48.3 (6.07)	64.6 (5.43)	28.75 (5.92)
4) Small → Large, Large → Small, Equal	20.0 (8.0)	56.25 (10.83)	21.25 (8.65)
5) Small → Large, Equal, Large → Small	3.75 (2.02)	37.5 (11.24)	11.25 (4.46)
6) Equal, Small → Large, Large → Small	20.00 (8.37)	27.5 (10.63)	6.25 (6.25)
Small → Large before Large → Small subgroup	14.6 (4.0)	40.4 (6.4)	12.9 (3.88)
Overall	31.46 (4.0)	52.50 (4.36)	20.83 (3.61)

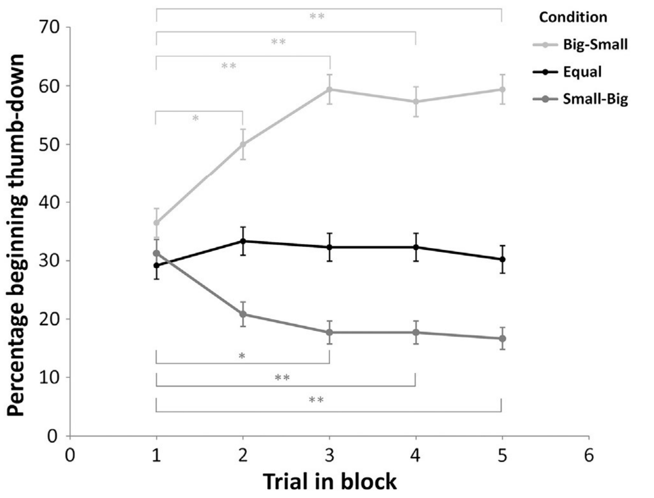

Fig. 3. Development of the initial grip position over the consecutive trials in each condition. * denotes $p < .05$, ** denotes $p < .01$. Whiskers denote standard error of the means.

in the current experiment, which discriminates between ESC and OCICP, is the Small → Large condition, where ESC predicts an initial thumb-down grip position, whereas OCICP predicts an initial thumb-up grip position. The results show that participants used the initial thumb-up position in 79.16%. This clearly speaks in favour of the OCICP.

Participants' preceding motor experiences influenced motor behaviour on different time scales. In this experiment, we demonstrated a significant influence of directly preceding trials as well as an influence of the preceding condition. While in the first trial of each condition, approximately the same percentage of participants used a thumb-down initial grip, a significant number of participants changed their initial grip position by the third trial at the latest. Given the data, the behaviour of significantly more participants followed the OCICP hypothesis in the second and subsequent trials of the Large → Small condition, just as the behaviour of significantly more participants followed the OCICP hypothesis in the third and subsequent trials of the Small → Large condition. However, the number of participants with an initial thumb-down grip position stayed the same in all trials of the Equal condition, independent of hole size (Fig. 3). We conclude that the evaluation of the preceding trial influences motor planning in a way predicted by the OCICP hypothesis. We assume that, on the first trial in the condition, participants estimated the motor cost associated with the task at hand. After having executed the first trial, an evaluation led a significant part of participants who had not followed the OCICP to change their initial grip position.

The preceding condition also influenced the initial grip position of the actual condition. Participants tended to use the type of grip that they used in the preceding condition. This demonstrates the tendency to stay with the successful motor planning procedure. Presumably, a significant number of participants did not anticipate a substantial change of motor costs when the condition changed.

4. General discussion

Our experiments shed new light on the processes involved in motor planning. We follow Cohen and Rosenbaum (2004) and suggest distinguishing two different processes, a cognitive-motor planning process that generates motor commands and a recall process that relies on previous experiences. The general idea is that by default, motor behaviour is governed by a recall process, which is computationally less costly than generating a new motor plan. The second idea is that motor planning processes can be described best by a criterion that has a function for movement goal achievement. We suggest that this criterion is OCICP.

4.1. Recall processes

We suggest that a substantial part of motor control is done using a recall process, which relates to one's individual motor experiences. On a very large time scale, motor experiences are accumulated over a lifespan. Everyday motor behaviours, such as walking, reaching, picking up and putting down familiar objects, are controlled by recall processes based on these long-term motor experiences. This recalled long-term motor experience is the foundation of the “habitual mode” of motor control. It is accountable for the biases found in experiments concerning motor planning processes. In experiment 1, we observed that the grip position was not changed by the vast majority of participants. We suggest here that this behaviour is controlled by the habitual mode. The idea of a “habitual system” that controls the movement was already formulated by Herbort and Butz (2011), who showed that grasping habits play an important role in movement planning. The habitual mode is used if and only if no specific demands require a cognitive-motor plan generating process. This interpretation is consistent with the discovery that the ESC is not found in movements where there is no precision demand (Rosenbaum, Cohen et al., 2006; Rosenbaum et al., 1996; Short & Cauraugh, 1999).

Besides the habitual mode, recall processes on a short time scale may also constrain motor behaviour. As shown in experiment 2, the immediately preceding trial influenced motor planning on a very short time scale, but the cumulative experience across trials in a preceding condition also had an influence on motor planning processes.

It may be debatable if the habitual mode is part of an active planning process executed by a “habitual system”, as Herbort and Butz (2011) suggest. There are two other possible alternatives. From a cognitive point of view, one could argue that grasping movements are highly automated and that (conscious) planning processes are not needed (Rosenbaum, Halloran, & Cohen, 2006). The dynamical systems perspective would explain the grasping behaviour by a directly perceived affordance (Gibson, 1979), which is to grab the object in a way that is determined by the task and the environmental constraints and which corresponds to an attractive state of the dynamical system that governs motor behaviour (Haken, Kelso, & Bunz, 1985). Independent of the favoured approach, we argue that for everyday actions without high attentional demand, motor behaviour is controlled in a habitual mode that runs without explicit cognitive-motor planning processes.

4.2. Plan generating processes

Plan generating processes come into play when the habitual mode of motor behaviour does not provide a satisfying solution. Rosenbaum, Cohen et al. (2006) state that “movements are planned first by specifying goal postures” (p. 20). Our experiments help to identify these “goal postures”. We could show that they are not necessarily the end states, but rather the “critical part” of the movement, where the critical part is the part of the highest precision demand within a movement sequence required to achieve the goal of the movement. Crucially, these findings suggest that it is not the precision hypothesis that explains the end-state-comfort effect, as suggested by Rosenbaum et al. (1996). Instead, optimal control in the critical part of the movement, that is, where it is most needed, rules cognitive-motor planning. This supports Rosenbaum et al.'s (2012) recent proposal that it is control and not comfort that constrains motor planning processes. The often demonstrated ESC turns out to be a side effect, caused by using pick-up-and-put-down tasks as an experimental paradigm, where the highest demand of precision is in the put-down part, which is at the end of the movement. OCICP leads to a functional explanation of motor planning processes. While an ESC effect has, to the best of our knowledge, no functional relevance, the functional relevance of OCICP is obviously the enhancement of speed or precision in the critical part of a movement through the use of a comfortable, mid-range position (Rosenbaum et al., 1996; Short & Cauraugh, 1999). These considerations were confirmed by a recent experiment of Hughes, Seegelke, and Schack (2012). In their experiment, the authors manipulated the precision demand in the beginning of a pick-and-put task and observed an initial state comfort in half of their participants.

Cohen and Rosenbaum (2011) distinguish between prospective and retrospective features of motor planning. In their concept, prospective features reflect the tendency of achieving a comfortable end state, while retrospective features reflect the tendency to grasp an object the same way as in the trial before. In light of our results, we do not support such a distinction. We would rather argue that the motor system tends to reduce cognitive-motor costs by solely controlling the movement in a habitual mode. Costs of cognitive-motor planning are only paid if the motor costs are too high, which means that the control of the movement is not sufficiently precise or that the energy spent is too high.

An open question is how to determine in which situation the motor control system can rely on the habitual mode and in which situation an explicit motor planning process takes control. As mentioned above, we assume that by default, movements are controlled in the habitual mode. Let us assume a situation where the habitual mode will not provide an acceptable result. It seems improbable that this result must always be experienced before motor planning process come into play. Rather, we suggest that in such cases a leading anticipation of the movement consequences, provided by a forward model (e.g., Jordan & Rumelhart, 1992), could trigger the motor planning processes before the movement is actually executed.

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