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Too much anticipation? Large anticipatory adjustments of grasping movements to minimal object manipulations

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ABSTRACT

When humans grasp objects, the grasps foreshadow the intended object manipulation. It has been suggested that grasps are selected that lead to medial arm postures, which facilitate movement speed and precision, during critical phases of the object manipulation. In Experiment 1, it has been tested whether grasp selections lead to medial postures during rotations of a dial. Participants twisted their arms considerably before grasping the dial, even when the upcoming dial rotation was minimal (5°). Participants neither assumed a medial posture at any point during a short rotation, nor did they assume any of the postures involved in short rotations in the opposite direction. Thus, grasp selections did not necessarily lead to specific postures at any point of the object manipulation. Experiment 2 examined the effect of various grasps on the speed of dial rotations. A medial initial grasp resulted in the fastest dial rotations for most rotation angles. Spontaneously selected grasps were more excursed than necessary to maximize dial rotation speed. This apparent overshot might be explained by participants' sensitive to the variability of their grasps and is in line with the assumption that grasps facilitate control over the grasped object.

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1. Introduction

Most objects can be grasped in different ways. This allows humans to choose grasps that facilitate the subsequent interaction with an object (for recent reviews see Herbort, 2013; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Wunsch, Henning, Aschersleben, & Weigelt, 2013). However, the selection of a suitable grasp is not trivial. It requires – among other things – the integration of information about the object, about the constraints and properties of the human body, and the relationship between object and body movements. Grasp selection for the interaction with objects is often studied with the bar transport task and its variations. These tasks require participants to grasp an object and rotate it in different directions. Thereby, participants usually twist the arm before grasping the object, which then leads to a medial arm posture (i.e. a posture in the middle of the arm's range of motion, Fig. 1) at the end of the object rotation. As medial postures are perceived as more comfortable, this finding has been termed "end-state comfort effect" (Rosenbaum et al., 1990).

A medial end posture characterizes object manipulations even in the presence of otherwise strong constraints on human movement. For example, when two objects have to be handled, medial end postures are assumed even if this requires executing asymmetric arm movements (Weigelt, Kunde, & Prinz, 2006). Likewise, participants prefer handling an object with the non-dominant hand when this leads to a medial end posture over handling an object with the dominant hand when this entails a non-medial end posture (Coelho, Studenka, & Rosenbaum, 2013; Johnson, 2000). Additionally, other factors (e.g. habitual grasps, task framing) studied so far affected the grasp only slightly or when the grasp selection had little influence on the postures assumed during the object manipulation (e.g. Herbort & Butz, 2011, 2012; Herbort, Butz, & Kunde, 2014; Hughes, Haddad, Franz, Zelaznik, & Ryu, 2011; Künzell et al., 2013; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Seegelke, Hughes, & Schack, 2011).

The reason for the finding that object manipulations usually involve and often end in medial arm postures has been explained by the combination of two hypotheses (Künzell et al., 2013; Rosenbaum, van Heugten, & Caldwell, 1996; Rosenbaum et al., 2012; Short & Cauraugh, 1999). First, it was assumed that participants select grasps that maximize control over the object. That is, being able to move the object as quickly (Rosenbaum et al., 1996) and precisely (Short & Cauraugh, 1999) as possible. Depending on the task, the need for precise control may be highest at the beginning of the rotation, during the rotation, or at its end (Hughes, Seegelke, & Schack, 2012; Künzell et al., 2013; Rosenbaum et al., 1996). This hypotheses is supported by several experiments. For example, participants who should rotate a handle adjusted the grasp more strongly in anticipation of the upcoming rotation when precision requirements were high (Rosenbaum et al., 1996). Likewise, when the need for precision was highest during early phases of the movement, participants tended to grasps the object initially with a medial grasp (Hughes et al., 2012; Künzell et al., 2013).

Whereas the first hypothesis suggests that grasps are selected that maximize the control over the object, the second hypothesis addresses how grasp selection could contribute to the maximization of control. It was assumed that movements can be controlled best with medial arm postures. Thus, grasp selection should ensure that the arm is in a medial posture when the precision demands are highest. This hypotheses has been addressed less frequently, but it also found empirical support. When participants were asked to oscillate a bar in a medial posture, they were quicker than when oscillating the bar in supine or prone postures (Rosenbaum et al., 1996).[1] Likewise, participants placed objects more precisely when holding them with a medial arm posture than with an uncomfortable arm posture (Short & Cauraugh, 1999).

In sum, the postures assumed during an object manipulation are thought to determine the grasp, because postures determine how fast and precise a movement can be controlled. In the remainder, the hypothesis that grasps are selected that lead to specific arm postures at some point during the object manipulation – either to maximize control or for other reasons – will be referred to as *posture-determined grasp selection*.

[1] Please note that the present nomenclature for arm posture deviates from Rosenbaum et al.'s (1996). Their 'medial', 'central', and 'lateral', corresponds to the terms 'prone', 'medial', and 'supine', respectively, in the present article.

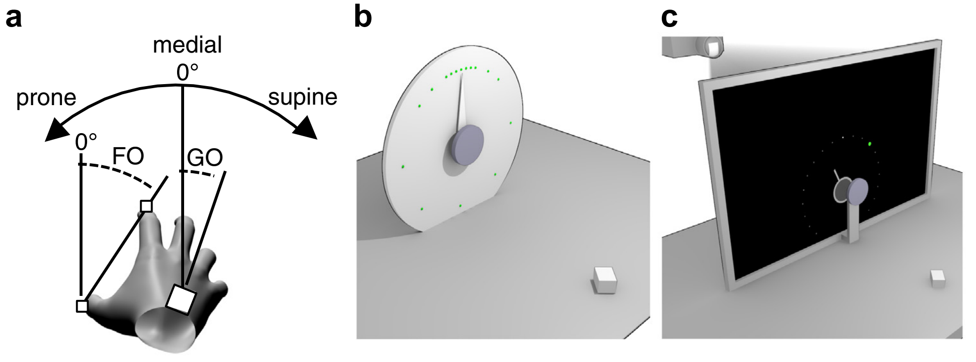

Fig. 1. Variables and apparatus. (a) The figure shows the placement of the markers (white squares) and the definition of the forearm and grasp orientation. (b and c) The figures illustrate the setup of Experiments 1 (b) and 2 (c).

A series of experiments in which participants were free to adjust the orientation of the grasp (e.g. when grasping a circular knob) casted doubt on posture-determined grasp selections hypothesis (Herbort & Butz, 2012; Herbort et al., 2014; Lardy, Beurier, & Wang, 2012; Mutsaarts, Steenbergen, & Bekkering, 2006; van der Vaart, 1995). These experiments suggested that the direction of the rotation is the primary determinant of the grasp selection. For example, in one experiment, participants had to grasp and rotate dials comparable to the volume control on a stereo (Herbort & Butz, 2010). Whereas the grasps selected for clockwise rotations differed considerably from those selected for counterclockwise rotations, the extent of the rotation had only a minor influence on the selection of the grasp. This finding hints at a situation in which the grasp might not be determined by the postures involved in the object rotation. Consider that rotation direction might also have a considerable effect on the grasps preceding very short rotations. In such cases, participants would grasp a to-be-rotated dial with a non-medial arm posture and might not return or pass through medial postures during dial rotation. If the right hand was used, short clockwise rotations would be carried out solely with prone arm postures and short counterclockwise rotations solely with supine postures. As both rotations would neither involve a medial posture nor share a single common posture, grasp selection could not be considered posture-determined. Please note that such a result could not be explained by participants' insensitivity to the task requirements (Hughes et al., 2012) or limited engagement in anticipatory planning (Cohen & Rosenbaum, 2004; Rosenbaum & Jorgensen, 1992) because grasps would be excursed stronger than necessary to assume a medial end posture.

The possible finding that grasp selections are no determined by the postures involved in the object manipulation would have implication for the hypotheses mentioned above. Either, the hypothesis that grasps maximize control is incorrect, the hypothesis that control is constrained by the arm posture is incorrect, or both hypotheses are incorrect.

The purpose of this paper is to test these hypotheses with two experiments. In Experiment 1, the posture-determined grasp selection hypothesis is tested. Experiment 2 follows up Experiment 1 by checking whether the selected grasps are optimal to control an object quickly and precisely.

To my knowledge, a case in which grasp selections resulted in object manipulations that did not involve medial postures at some point has not yet been documented. However, this might be due to the large rotations required in previous experiments. For example, in the bar transport task or handle rotation task, participants had to rotate objects usually by 90° or 180°. Given the extent of these rotations, it is not surprising that medial postures are assumed at some point of the object rotations. In dial rotation tasks, rotations of smaller extent were probed (usually between 30° and 60°), but even these extents were so large that the arm returned to or moved through a medial position by the end of the rotation (Herbort et al., 2014; Lardy et al., 2012; Mutsaarts et al., 2006; van der Vaart, 1995). The goal of Experiment 1 was to test whether participants grasp an object with a non-medial forearm orientation without returning to a medial forearm orientation during very short object rotations. To this end, the effect of minimal rotations of a dial on the orientation of the forearm at the beginning and the end of the dial rotation movement was examined. If the arm posture before a minimal dial rotation was excursed further than necessary to reach a medial end posture, the posture-determined grasp selection hypothesis could be rejected. Alternatively, the intention to rotate the dial only a little might result in correspondingly small adjustments of the forearm orientation during grasping, leading to a medial posture at some point of the rotation. Such a finding would support the posture-determined grasp selection hypothesis.

2. Experiment 1

2.1. Method

2.1.1. Participants

Nine women and three men participated in the study after giving informed consent. The mean age of the participants was 24 (SD = 4) years. All were right handed according to a German Translation of the handedness scale of Coren's (1993) Lateral Preference Inventory (handedness score: $m = 4$, sd = 0).

2.1.2. Apparatus and stimuli

Fig. 1b shows the setup of the experiment. Participants were seated in front of a table. On the table, a dial (diameter 8 cm) was installed that could be used to rotate a plastic pointer protruding 14.5 cm from the dial's axis of rotation. Behind the dial and the pointer was a circular white board on which 16 green LEDs (5 mm) were fixed on an imaginary circle (diameter 30 cm). The positions of the LEDs were 180°, 135°, 90°, 45°, 30°, 15°, 10°, 5°, 0°, −5°, −10°, −15°, −30°, −45°, −90°, and −135°, with 0° corresponding to the 12 o'clock position and negative angles to the clockwise direction. The dial was connected to a motor that continuously pulled back the dial and pointer to the 0° position with a torque of 0.015 Nm. A start button (3 cm × 4 cm × 2.5 cm) was positioned 35 cm in front of the dial and served as resting position for the hand.

2.1.3. Procedure

Each trial started with the pointer at 0°. The participant was instructed to press the start button with index finger and thumb. Once the start button was continuously pressed for one second, the rotation angle was indicated by illuminating all LEDs between 0° and the required rotation angle along the path of the pointer. For example, a rotation by 90° was indicated by illuminating the LEDS at 0°, 5°, . . ., 90°; a rotation angle of −270° was indicated by illuminating the LEDs 0°, 5°, ..., 180°, −135°, and −90° This was necessary to disambiguate clockwise and counterclockwise rotations with identical pointer end positions (e.g. the 90° and −270° rotation). Additionally, a beep was played (1760 Hz, 25 ms). The participant then grasped the dial with the right hand and rotated the pointer to the lit LED. Once the pointer was within 1.5° of the target LED for 100 ms, the LED flashed three times. This was the sign for the participant that the target was successfully reached and that the next trial could be initiated by grasping the start button again.

The forearm orientation of the medial posture was operationalized as the forearm orientation that is preferably assumed when the object needs to be grasped but not manipulated. To asses the medial forearm orientation, grasp-and-hold trials were included, in which participants were asked to grasp the dial and hold it without rotating it. These trials were indicated by illuminating the 0° LED. Once the participants' index finger and thumb sensors stayed within 5 cm of the dial for 2 s, the 0° LED went out, informing participants to release the dial. The participants were instructed to release the dial after rotating or holding it without actively repositioning the pointer back at the 0° position, to grasp the dial firmly, to not readjust the grasp, and to use the right hand. No specific instruction were given with respect to movement speed and accuracy.

During the experiment, participants had to rotate the dial by the following rotation angles: 270°, 225°, 180°, 135°, 90°, 45°, 30°, 15°, 10°, 5°, 0° (grasp-and-hold), −5°, −10°, −15°, −30°, −45°, −90°, −135°, −180°, −225°, and −270°. The experiment consisted of 10 blocks of 63 trials, in which each rotation angle was repeated three times. The order of trials in each block was randomized. Altogether, each rotation angle was presented 30 times.

2.1.4. Data recording and analysis

The movement of the hand and the dial were recorded at 100 Hz with an electromagnetic motion tracker (Ascension TrakStar). One sensor was fixed to the distal end of the forearm of the participants, one sensor was attached to the fingernail of the index finger, one sensor was attached to the thumbnail, and one sensor was attached to the dial's axis. For data analysis, the data were smoothed with a 2nd-order bidirectional Butterworth filter (20 Hz) and resampled to 1000 Hz. The orientation of the forearm (FO) as recorded with the forearm sensor was extracted. A forearm orientation of about 0° is assumed when the hand and forearm rested flat on the table (Fig. 1a). When the participants were holding the start button, FO was on average −37° (sd = 11°). FO was extracted before and after the dial rotation (FO_{BEFORE}, FO_{AFTER}). FO_{BEFORE} was extracted at the first moment after which index finger and thumb stayed within 1 cm of the position they would assume when the dial rotation rate reached 10% of its maximum. FO_{AFTER} was extracted when the dial stayed within 1.5° of the target for 100 ms.[2] Except for the 109 Trials (2.1%), for which no data could be extracted, all trials were included in the analysis.

2.2. Results

2.2.1. Forearm orientation before rotation

The mean forearm orientation before and after the rotation were computed for each participant and each combination of rotation angle and block. The factor block was included, because grasp selections might change over the course of an experimental session (c.f. Künzell et al., 2013; Seegelke, Hughes, Knoblauch, & Schack, 2013). Fig. 2a shows FO_{BEFORE} and FO_{AFTER} averaged over blocks. Data split by block is provided as Supplementary Fig. S1. The mean forearm orientation before and after the dial rotation were submitted to a within-subject ANOVA with factors rotation angle (−270°, −225°, ..., 270°) and block (1, 2, ..., 10).[3] The ANOVA on FO_{BEFORE} revealed a significant main effect of rotation angle, $F(20,220) = 157.6$, $p < .001$, $\eta_p^2 = 0.935$. Additionally, there was a main effect of block, $F(9,99) = 3.0$, $p = .044$, $\eta_p^2 = 0.212$. Rotation angle and block interacted, $F(180,1980) = 2.3$, $p = .026$, $\eta_p^2 = 0.174$.

Descriptively, the FO_{BEFORE} was about 7° more supine in the first than in the last block and the effect of the rotation angle on FO_{BEFORE} was larger in the first than in the last block. This was statistically supported by a post hoc ANOVAs comparing each of the first nine blocks to the last block (keeping the within-subject factor rotation angle). The post hoc ANOVA comparing the first and last block revealed main effects of block, $F(1,11) = 10.8$, $p = .007$, $\eta_p^2 = 0.496$, and a significant interaction, $F(20,220) = 4.7$, $p = .003$, $\eta_p^2 = 0.297$. The post hoc ANOVA comparing the third and last block revealed a significant interaction between rotation angle and block, $F(20,220) = 2.6$, $p = .043$, $\eta_p^2 = 0.191$. No other significant effects of block or interactions between block and rotation angle were found (all $ps \geqslant .130$). Consistent effects of rotation angle were found for all post hoc ANOVAs (all $ps < .001$).

Next, the effect of minimal rotations on FO_{BEFORE} was tested. A within-subject ANOVA with within-subject factor block (1, ..., 10) and rotation angle (5° vs. −5°) was used to compare FO_{BEFORE} of 5° rotations with FO_{BEFORE} of −5° rotations. Similar ANOVAs were used to compare the grasp-and-hold condition (0°) with the −5° rotation and the 5° rotation condition (−5° vs. 0°; 0° vs.

[2] Besides FO, the orientation of the grasp was extracted, defined as the angle between thumb and index finger in the coronal plane, which assumed 0° when the index finger was directly above the thumb. However, as the forearm orientation was highly correlated with the grasp orientation, only the forearm orientation is discussed in the manuscript. The participant-wise Pearson correlation between the forearm orientation and grasp orientation was $r = .992$ (sd = .006) before the rotation and $r = .977$ (sd = .012) after rotation.

[3] Greenhouse-Geisser corrected p-values but uncorrected degrees of freedom are reported for ANOVAs throughout the paper. Post-hoc tests were not corrected for multiple comparisons for the following reasons: Tests following up effects of block or an interaction between block and rotation angle were conducted to check if the data could be collapsed over blocks. Correcting for multiple comparisons would make these tests overly conservative. Test following up the effect of rotation angle were not corrected because significant effects were predicted for all tests.

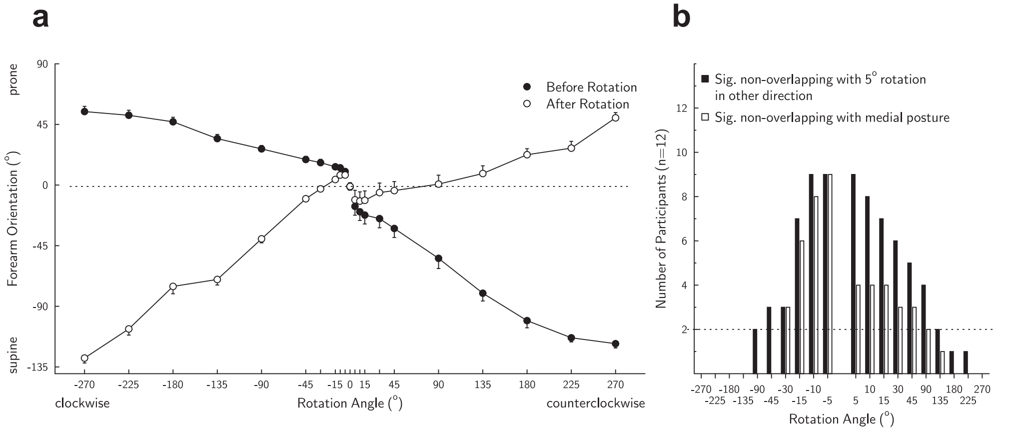

Fig. 2. Results of Experiment 1. (a) The figures shows average forearm orientations before and after dial rotations in Experiment 1. Error bars show between subject standard errors. The horizontal line indicates the FO_{AFTER} of grasp-and-hold trials (i.e. medial forearm orientation) (b) The figure shows for how many participants the forearm orientations assumed throughout a specific rotation did not overlap with the forearm orientations assumed during a 5° rotation in the opposite direction (black) or the medial forearm orientations (assessed at the end of grasp-and-hold trials; white). Frequencies surpassing the dashed lines are significantly larger than expected by chance ($\alpha = .05$).

5°). Table 1 shows the results of the ANOVAs. The forearm orientations assumed before 5° differed from those before −5° rotations. Both differed from the forearm orientation when grasping the dial without the intent to rotate it. No significant interactions between block and rotation angle were found. Descriptively, the reported effects were larger in the first block than in the remaining blocks but persisted throughout the experiment (c.f. Supplementary Fig. S1). The effects of the rotation angles also persisted when the data of the first block was removed from the analysis, all $ps \leqslant .002$.

2.2.2. Forearm orientation after rotation

A comparable pattern of results was found for FO_{AFTER}. A within-subject ANOVA with factors rotation angle (−270°, −225°, ..., 270°) and block (1, 2, ..., 10) revealed a significant effect of rotation angle, $F(20,220) = 116.2$, $p < .001$, $\eta^2_p = 0.914$, and block, $F(9,99) = 5.3$, $p = .002$, $\eta^2_p = 0.324$. The interaction failed to reach significance, $F(180,1980) = 1.8$, $p = .090$, $\eta^2_p = 0.139$. Post-hoc ANOVAS comparing each block to the last block (keeping the factor rotation angle) revealed significant differences in the overall FO_{AFTER} between blocks 1 to 4 and the last block (all $ps \leqslant .037$) but no significant interaction (all $ps \geqslant .079$). Descriptively, the postures assumed at then end of the rotation got more supine throughout the experiment.

A within-subject ANOVA with within-subject factor block (1, ..., 10) and rotation angle (5° vs. −5°) was used to compare FO_{BEFORE} of 5° rotations with FO_{BEFORE} of −5° rotations. Similar ANOVAs were

Table 1
ANOVAs on FO_{BEFORE} and FO_{AFTER}.

Variable	Comparison	Main effect rotation angle			Main effect block			Interaction angle x block		
		$F(1,11)$	p	η^2_p	$F(9,99)$	p	η^2_p	$F(9,99)$	p	η^2_p
FO_{BEFORE}	−5° vs. 5°	21.5	<.001	.662	1.9	.145	.148	2.1	.090	.161
	−5° vs. 0°	28.4	<.001	.721	2.3	.066	.175	1.2	.322	.097
	0° vs. 5°	16.2	.002	.596	2.8	.044	.206	1.0	.416	.084
FO_{AFTER}	−5° vs. 5°	9.9	.009	.474	2.7	.066	.194	1.7	.178	.132
	−5° vs. 0°	11.7	.006	.515	3.4	.012	.235	1.3	.275	.107
	0° vs. 5°	8.1	.016	.425	3.6	.019	.248	1.0	.432	.081

used to compare the grasp-and-hold condition (0°) with the −5° rotation and the 5° rotation condition (−5° vs. 0°; 0° vs. 5°). Significant effects of rotation angle were found for all three comparisons (Table 1). This means that even the end postures, which were the postures closest to the medial positions in the 5° rotations, differed significantly from the medial posture. That is, the postures used in −5° clockwise rotations were more prone than the medial posture throughout the entire rotation. Likewise, all postures used in the 5° counterclockwise rotation were more supine than the medial posture. This also implies that small rotations in different directions did not share a single posture. Hence, grasp selections did not lead to a specific posture at any point of the dial rotation.

2.2.3. Common postures in object manipulations

The inspection of the data revealed that for some participants, relatively large rotations neither included the forearm orientation used to grasp and hold the dial nor the forearm orientations used for rotations in the other direction. For others, this was not the case. To express these individual differences, data was split by participant and rotation angle. One sided t-test were used ($\alpha = .05$) to tested if FO_{AFTER}s after clockwise rotations were more prone than the FO_{AFTER} of the 5° counterclockwise rotation or the FO_{AFTER} of grasp-and-hold trials. For counterclockwise rotations, it was tested whether FO_{AFTER}s were more supine than the FO_{AFTER} after the −5° clockwise rotation or the 0° rotation. A significant effect indicates that the postures involved in a particular rotation of a particular participant did not include the medial posture or any postures used during a 5° rotation in the other direction, respectively. Fig. 2b shows that this was the case for 9 out of 12 participants for at least some rotations. The chart also shows that even larger rotations of some participants did not involve the medial posture. For rotation angles in which the bars surpass the dashed line the number is significantly higher than could be expected by chance (one-sided binomial test, $\alpha = .05$). Supplementary Fig. S2 shows the differences between FO_{AFTER}s and the medial posture, as well as differences between FO_{AFTER}s and the FO_{AFTER}s of a 5° rotation in the opposite direction for individual participants.

2.3. Short discussion

Experiment 1 was conducted to test the hypothesis that grasps are selected that lead to medial arm postures at some point of a dial rotation. This hypotheses was not supported by the data. Participants used rather different grasp postures before short clockwise and counterclockwise rotations. As a consequence, the forearm orientation was more prone than the medial grasp-and-hold posture throughout short clockwise rotations and more supine than the medial posture throughout short counterclockwise rotations. This implies that short clockwise and short counterclockwise rotations did not share a single posture. Thus, grasp selection did not lead to medial – or any other specific posture – at any stage of the object manipulation. Please note that adjustments were stronger than could be expected based on the posture-determined grasp selection hypothesis, indicating that participants grasp behavior did not arise from a lack of anticipatory planning (Cohen & Rosenbaum, 2004; Herbort & Butz, 2011; Künzell et al., 2013).

The findings replicate and extend previous research. As far as larger rotations are concerned, the present data replicate previous experiments, in which participants could continuously adjust their grasp. Regardless of whether participants had to rotate fixed circular or hexagonal dials (Herbort & Butz, 2010; Lardy et al., 2012; Mutsaarts et al., 2006; van der Vaart, 1995) or rotate freely movable objects with a circular knob (Herbort & Butz, 2012; Herbort et al., 2014; c.f. Zhang & Rosenbaum, 2008; for a review see Herbort, 2013), the experiments showed an apparent discontinuity between grasp selections for clockwise and counterclockwise rotations. However, previous reports of larger rotations could be accommodated to the posture-determined grasp selection hypothesis (Lardy et al., 2012), because all rotations involved medial postures either at the end or during the rotation. By contrast, the present data suggests that the hypothesis cannot account for shorter object manipulations. Rather, the data support the notion that the direction of the dial rotation *per se* affects grasp selection considerably (Herbort, 2013; Herbort & Butz, 2012). This becomes apparent when comparing how the grasp is affected by rotations with minimal extent in different direction and rotations of different extents in the same direction. The difference in forearm orientation preceding the −5° and the

5° corresponds to the difference between the forearm orientations assumed before rotations of 5° and over 45° or −5° and −135°.

Finally, it has been shown that participants adapt grasp selection to task requirements over the course of an experimental session. For example, grasp selections for sequential object manipulations increasingly reflect demands of later manipulation steps (Seegelke et al., 2013). Likewise, grasp selections are influenced by previously executed tasks (Künzell et al., 2013). In the present experiment, grasp selections were initially more excursed, than during later blocks. This effect was larger before counterclockwise rotations, resulting in overall more supine grasps in the first block. Two conclusions can be drawn from these findings.

First, participants were apparently able to adjusted their grasp selections to the task and did so in the first blocks (c.f. Seegelke et al., 2013). Second, grasp selection remained constant after a few blocks until the end of the experiment. This suggests that participants might have adapted as good as possible to the task. At this point, it can only be speculated which factors drove the adaptation process. An experiment, in which participants manipulated freely moveable objects with a knob similar to the knob in the present experiment, hints at a possible explanation (Herbort et al., 2014). In their experiment, the grasps used to rotate the object got increasingly excursed, especially when the object was comparatively heavy. By contrast, the excursion of grasps decreased in the current Experiment 1, in which the knob was supported and had very low inertia. It can be speculated that factors such as the object's weight, inertia, or whether it is freely movable partially determine the most suitable grasps for specific object manipulations. Participants grasps might have been initially tuned to tasks that were more demanding with respect to such factors than the task in the current experiment, but less demanding than the task used by Herbort et al. (2014). As a result, grasp excursion might have decreased in the first blocks of Experiment 1 but increased when handling the heavier; freely movable object.

In summary, it has been assumed that grasps are selected that enable fast and precise control of object manipulations (Künzell et al., 2013; Rosenbaum et al., 2012). As the control over an object was thought to be maximal when it is held in a medial arm posture, control was thought to be maximized by selecting grasps that lead to medial postures at critical phases of the movement (Künzell et al., 2013; Rosenbaum et al., 1996, 2012; Short & Cauraugh, 1999). In contrast to this reasoning, Experiment 1 showed that neither a medial posture nor any other specific posture is necessarily assumed during object manipulations. Three possible conclusions can be drawn from this result. First, grasp selections facilitate control. However, control over the object is determined by other factors than the arm postures during the object manipulation. Second, grasp selection does not facilitate control. Nevertheless, the control over the object depends on the arm postures during the object manipulation. Third, neither are grasps selected that optimize control, nor do the arm postures during the object manipulation determine control.

3. Experiment 2

The purpose of Experiment 2 was to test which grasps are best suited to control the dial quickly and precisely and whether spontaneously selected grasps facilitate control. Participants engaged in two different tasks. In some trials, participants were instructed to use specific grasp postures (grasp-determined condition). The grasp postures that resulted in the fastest dial rotations could be considered optimal to control the dial. These optimal grasps postures were compared to the grasp postures that were selected spontaneously (i.e. in trials in which participants could freely choose a grasp, grasp-free condition).

In Experiment 2, control is measured in terms of the duration of the rotation, even though it has been suggested that grasps for object manipulations enhance the combined speed and accuracy of the object manipulation. Previous studies either used movement speed (Rosenbaum et al., 1996) or precision (Short & Cauraugh, 1999) to assess control. As human movements, including forearm rotations, are subject to the speed-accuracy trade off (Fitts, 1954; Meyer, Abrams, Kornblum, Wright, & Keith Smith, 1988; Novak, Miller, & Houk, 2000), it seems justified to quantify control as the speed of dial rotations with a fixed, high accuracy demand.

Finally, it has been suggested that grasps are planned for fast and precise object manipulations by default (i.e. even when these constraints have not been made explicit, Rosenbaum et al., 2012). This reasoning is reflected in the instructions used in previous studies that did not stress movement speed (e.g. Herbort & Butz, 2012; Künzell et al., 2013; Rosenbaum et al., 1996). Hence, participants were likewise not asked to move as fast as possible in Experiment 2.

3.1. Method

3.1.1. Participants

Fifteen women and 5 men participated in the study after giving informed consent. The mean age of the participants was 30 (SD = 9) years. All were right handed according to a German Translation of the handedness scale of Coren's (1993) Lateral Preference Inventory (handedness score: $m = 3.8$, sd = 0.6).

3.1.2. Apparatus and stimuli

Fig. 1c shows the setup of the experiment. The geometric layout was similar to Experiment 1 but the technical implementation was different. Participants were seated in front of a table. On the table, the dial used previously (diameter 8 cm) was installed 17 cm above the table surface. The dial was not connected to a motor. A back projection screen (80 cm × 50 cm) was placed 6 cm behind the dial. A grasp element (3.2 cm × 4.8 cm × 2.6 cm) was positioned 30 cm in front of the dial and served as resting position for the hand.

During the trial, a ring of grey dots (4 mm) centered around the dial at distance of 5 cm was shown. The spacing between dots was 15° and dots ranged from −135° to 135° (where 0° corresponds to the 12 o'clock position). The dial orientation was indicated by a white cursor (3 mm) moving on the ring. The target was displayed as a green dot (6 mm) on the ring. In trials in which the grasp orientation was pre-determined, a grey disc from which a grey line protruded (10 cm) was displayed. The position of this stimulus was adjusted before the experiment so that the ring appeared centered on the dial from the view of the participant.

3.1.3. Procedure

Each trial started with the onset of the ring of dots and the cursor at 0°. In grasp-determined trials, the disc with the protruding line was also displayed. The participant was instructed to grasp the start element with the index finger and thumb. Once the start element was continuously held for 500 ms, the target appeared and a short beep was played (1760 Hz, 25 ms). The participant then grasped the dial with the right hand and rotated the cursor to the target. In trials in which the grasp was predetermined, participants were asked to align their index finger with the protruding line. The index finger position was used as a proxy for the grasp orientation, because it was found to be highly correlated with grasp orientation in Experiment 1 and because it allowed for individual placement of the thumb. Once the cursor was within 2° of the target for 100 ms, the screen went black. If the angle between dial axis and index finger differed by more than 20° from the instructed index finger position, the message ("BITTE GENAUER GREIFEN!", German for "grasp more accurately, please") appeared in red ink. Otherwise a green message praised the performance ("Gut gemacht!", German for "good job"). Either message was shown for 500 ms. This was the sign for the participant that the cursor was moved to the target and that the next trial could be initiated by grasping the start element again. The participants were instructed to grasp the dial firmly, to not readjust the grasp, and to use the right hand. No specific instruction were given with respect to movement speed and accuracy.

Six different targets had to be reached during the experiment (−135°, −45°, −15°, 15°, 45°, 135°). Index finger positions of 75°, 50°, 25°, 0°, and −40° were instructed for clockwise rotations, where 0° corresponds to the 12 o'clock position, and negative values to the clockwise direction and thus more supinated grasp). Index finger positions of 25°, 0°, −40°, −80°, and −120°, were instructed for counterclockwise rotations. Different ranges of index finger positions were used for clockwise and counterclockwise rotations to avoid extreme joint configurations but still cover a broad range of grasp orientations around those that were typically selected in Experiment 1. The range of prone index finger positions was more narrow because the difference between the 0° grasp orientation and the most prone grasps was smaller than the difference between the 0° grasp orientation and the most supine grasps in Experiment 1.

At the beginning of the experiment, the participants were familiarized with the task by administering 5 grasp-determined and 5 grasp-free trials. Trials were drawn randomly from the pool of trials that could appear in each condition. Then 24 blocks of 30 trials were administered. In each block, either only grasp-determined trials were presented (one repetition of each combination of rotation angle and index finger position) or grasp-free trials were presented (five repetitions of each target angle). Each block was preceded by two warm-up trials that were not analyzed. Thus, altogether 720 trials were collected (20 repetitions of each trial type) for analysis or 778 trials altogether. The blocks were separated by self-paced breaks. For half of the participants, one grasp-free block was alternated with five successive grasp-determined blocks, whereas for the other half, five successive grasp-determined blocks were alternated with one grasp-free block. Trial order and the assignment of participants to a specific block order was random. The experiment took approximately one hour.

3.1.4. Data recording and analysis

Data recording was similar to Experiment 1 except for a sampling rate of 50 Hz, which was necessitated by the sensor robustness required to present smooth online feedback. The forearm orientation FO_{BEFORE} was extracted at the first moment after which index finger and thumb stayed within 1 cm of the position they would assume when the dial rotation rate reached 10% of its maximum. The onset of grasping was defined as the moment when the tangential velocity of the forearm first exceeded 10% of the peak velocity. The duration from the onset of grasping to the extraction time point before dial rotation (as defined above) was defined as the movement time for grasping (MT_{GRASP}). The duration from the extraction time point before the dial rotation to the first time point after which the dial stayed within 2° of the target for at least 100 ms was defined as the movement time for rotation (MT_{ROT}). The absolute error (AE) was defined as the absolute deviation of the cursor from the target at the end of the rotation.

Trials that could not be segmented were excluded from analysis (423 or 3.0%). Additional, trials were excluded in which the forearm orientation at the time of grasping, or the duration from stimulus onset to task completion, deviated more than three standard deviations from the participants' and respective conditions' mean (61 and 87 of the segmented trials, respectively).[4] Outliers were distributed evenly across experimental conditions (ranging between 0.2% and 1.8%). In total, 564 trials (3.9%) were excluded.

3.2. Results

3.2.1. Grasp orientations

Fig. 3 shows FO_{BEFORE} of grasp-free and grasp-determined trials. An ANoVA on the grasp-free trials with within-subject factor rotation angle (−135°, −45°, −15°, 15°, 45°, 135°) revealed a significant main effect of rotation angle, $F(5,95) = 59.4$, $p < .001$, $\eta_p^2 = 0.758$. When participants were allowed to freely choose a grasp, the forearm orientation depended on the upcoming rotation. The grey data points in Fig. 3 depict the FO_{BEFORE}s resulting from instructing the various index finger positions. These grasp orientations sampled a range of postures surrounding the freely selected grasps. Average FO_{BEFORE}s for specific index finger positions but different rotation angles differed by less than 5°. Please note that the forearm orientation has a smaller range than the instructed index finger positions because the placement of the fingers is only partially accomplished by forearm rotations (Herbort & Butz, 2010; Marotta, Medendorp, & Crawford, 2003).

As a manipulation check, it was tested whether different index finger positions resulted in different FO_{BEFORE}s. For each rotation angle, an ANOVA with within-subject factor index finger position was conducted. For clockwise rotations, the factor levels were 75°, 50°, 25°, 0°, and −40°, for counterclockwise

[4] Please note that trials were included, in which the participants were informed to grasp more accurately after completing the rotation. As the analysis focuses on the forearm orientation, a criterion relative to the participants' average forearm orientation was used. The following analysis would yield similar results and lead to identical conclusions if only trials wee included in which participants adhered to the finger placement criterion used to deliver online feedback.

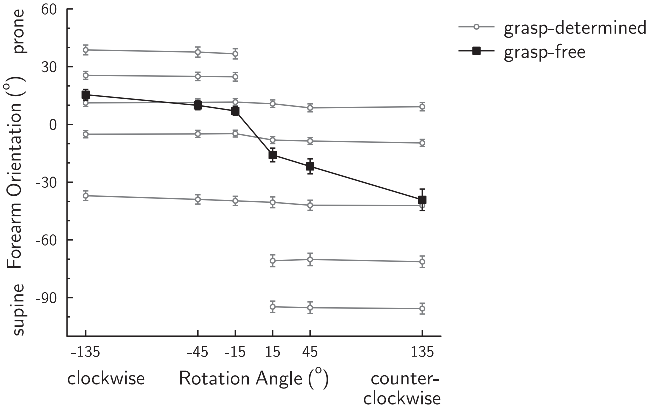

Fig. 3. Grasp selection in Experiment 2. The figure shows the forearm orientations at grasping when participants were allowed to freely select a grasp (black) and the forearm orientations adopted when the grasp was determined. The grey lines refer to the index finger positions from −120° (bottom) to 75° (top). Error bars show between subject standard errors.

rotations, the factor levels were 25°, 0°, −40°, −80°, and −120°. Additionally, a contrast analyses comparing adjacent index finger position were conducted (75° vs. 50°, 50° vs. 25°, and so on). For each rotation angle, the index finger position significantly affected FO_{BEFORE} (all *ps* < .001). Likewise, for each rotation angle, each pair of adjacent index finger positions was associated to significantly different FO_{BEFORE}s (all *ps* < .001). Thus, the instruction of a different index finger positions effectively caused participants to grasp the dial with different forearm orientations.

3.2.2. Duration of grasping, duration of rotation, and absolute errors

Next, it was tested whether different grasps affected the duration of a grasping movement, the duration of the dial rotation, and the accuracy of the dial rotation. Fig. 4 shows MT_{GRASP}, MT_{ROT}, and AE as a function of the forearm orientations in the grasp-determined trials (filled shapes). Additionally, the respective values for the grasp-free condition are plotted as white shapes. Their horizontal positions correspond to the FO_{BEFORE} assumed in grasp-free trials.

Each variable was submitted to ANOVAs with within-subject factor index finger position. For clockwise rotations, the factor levels were 75°, 50°, 25°, 0°, and −40°, for counterclockwise rotations, the factor levels were 25°, 0°, −40°, −80°, and −120°. The ANOVAS were conducted individually for each rotation angle. The results are listed in Table 2. The ANOVAs revealed that the orientation of the grasp affected how quickly the dial could be grasped and how long it took to rotate the dial. The AE was virtually unaffected by the grasp and ranged between 0.8° and 0.9°. The mean AE and MT_{ROT} of the different experimental conditions were positively correlated, $r = .352$, $t(34) = 2.2$, $p = .035$. Thus, dial rotations in conditions with higher rotation times tended to be less accurate and vice versa. This implies that effects on rotation times are not the result of a speed-accuracy trade-off.

Two findings are noteworthy. First, the quickest average grasps and rotations were observed with a forearm orientation of on average −7° for almost all rotation angles. Thus, participants were fastest when they did not adjust the grasp to the rotation angle. Second, the relationship between FO_{BEFORE} and MT_{ROT} can be described as an asymmetric u-shape. Consider the 135° rotation depicted in Fig. 4f. Participants were fastest with an FO_{BEFORE} of about −10°. More supine FO_{BEFORE}s resulted in only slightly slower rotations. By contrast, when FO_{BEFORE} was just about 20° more prone, the duration of the rotation was considerably prolonged. Analogous pattern of results were found for all rotation angles. To quantify this asymmetry, the rate of increase in MT_{ROT} from the second most prone to the most prone grasp and the second most supine to the most supine grasp (difference of MT_{ROT}/difference in FO_{BEFORE}) were compared with t-tests. The t-tests were conducted individually for each rotation angle. The tests revealed significant differences for the rotation angles −135°, 15°, and 135° (all $ps \leqslant .030$) and marginally significant differences for the rotation angles −15°, and 45° (all $ps \leqslant .059$).

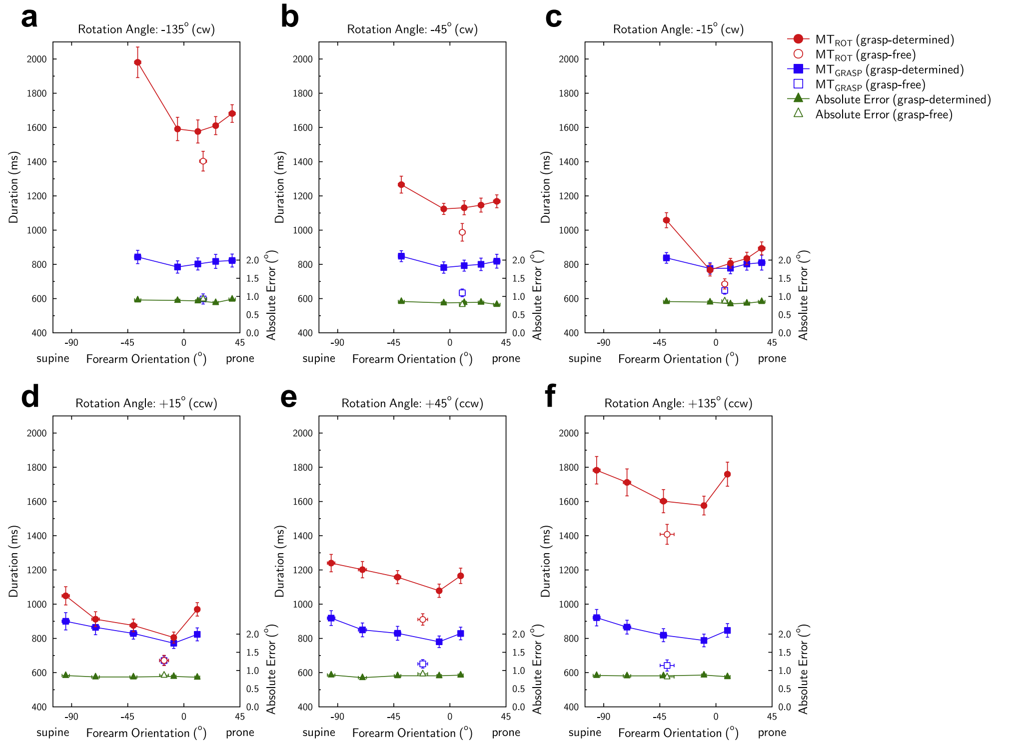

Fig. 4. Effect of grasp on movement duration and precision. The figures show MT_{GRASP}, MT_{ROT}, and AE by the average FO_{GRASP} assumed for the different instructed index finger positions of the grasp-determined condition (filled). Each data point corresponds to a specific instructed index finger position. The white isolated points refer to the average MT_{GRASP}, MT_{ROT}, and AE (y-axis) as well as the average FO_{GRASP} (x-axis) in the grasp-free condition. Error bars shows standard errors of the mean.

Table 2
ANOVAs on MT_{GRASP}, MT_{ROT}, and AE by rotation angle.

Rotation angle	MT_{GRASP}			MT_{ROT}			AE		
	$F(4,76)$	p	η_p^2	$F(4,76)$	p	η_p^2	$F(4,76)$	p	η_p^2
−135°	5.9	<.001	.235	24.6	<.001	.565	1.4	.258	.067
−45°	5.7	.005	.230	8.7	<.001	.314	1.1	.378	.053
−15°	8.1	<.001	.299	27.2	<.001	.589	1.0	.413	.049
15°	11.7	<.001	.381	15.7	<.001	.452	0.5	.713	.026
45°	24.6	<.001	.564	9.9	<.001	.343	1.0	.414	.049
135°	20.9	<.001	.523	8.8	<.001	.318	0.3	.875	.014

3.2.3. Optimal grasp selection

Fig. 4 shows that the freely chosen grasps were generally more prone than the grasp yielding the fastest movements for clockwise rotations. For counterclockwise rotations the reverse was found. Paired t-tests were used to compare FO_{BEFORE}s of grasp-free trials with FO_{BEFORE}s that were associated with the fastest grasping and rotation movements in the grasp-determined condition. The tests were conducted individually for each rotation angle. For each rotation angle, the freely chosen grasp was excursed more against the direction of the upcoming rotation than the grasp associated with the fastest grasping movements (all $ps \leqslant .008$). Except for the $-135°$ rotation, the freely chosen grasp was also more excursed than the grasp associated with the fastest rotation movements (all $ps \leqslant .008$). In sum, when twisting the arm during the grasping movement, participants consistently overshot the grasp orientation that would have minimized the duration of both, the grasping movement and the dial rotation.

3.3. Short discussion

The aim of Experiment 2 was to test how grasp selections affect the control over the dial, quantified by the time needed to rotate the dial. It was found that the grasp orientation affected both, the time necessary to grasp and rotate the dial. Thereby, two unexpected observations were made. First, the grasps that resulted in the fastest average dial rotations depended little on the upcoming dial rotation. A medial grasp resulted almost always in the fastest rotations. Second, an asymmetric effect of the grasp orientation on the rotation duration was found. These findings suggests that the direction of the rotation *per se* affects the efficiency of a grasp. Finally, participants excursed their arms stronger during unconstraint grasping movements than would be necessary to produce the quickest possible rotation or grasping movements. A possible explanation for these apparent overcompensations will be offered in the general discussion.

Interestingly, freely chosen grasps resulted in faster grasping movements and dial rotations than comparable instructed grasps. This difference may be attributed to the fact that participants controlled their grasp more precisely when the grasp was predetermined. This was reflected by the within-subject and within-condition standard deviations of the forearm orientation before rotations, which were on average 6.8° when the grasp was predetermined, but 12.5° when the grasp could be freely chosen. The slower grasping movements may have carried over to the dial rotation movements.

The present results differ from previous reports of the effects of posture or grasp selection on performance. Rosenbaum et al. (1996) reported that participants could carry out faster oscillatory pronation and supination movements in medial as compared to prone or supine postures. In this respect, our data replicate the earlier findings. However, whereas the posture affected pronation and supination movements alike in Rosenbaum et al.'s experiment, dial rotations involving pronations of the arm could be executed faster with the most supine postures than with the most prone postures and vice versa in the present experiment. This difference most likely resulted because the oscillation task biased participants to execute pronations and supinations with the same speed, as suggested by Rosenbaum et al. (1996), whereas no such constraint was imposed by the present task.

Short and Cauraugh (1999) asked participants to grasp a dowel and push it horizontally on a mark on a wall. When participants were instructed to use a grasp that resulted in a comfortable end-state, participants positioned the dowel closer to the mark then when using a grasp resulting in an uncomfortable end-state. This suggests that a medial end-posture facilitates control (c.f. Rosenbaum et al., 1996, 2012). By contrast, the present results suggest that a medial initial grasp may be best suited when executing rotations of various extents. These differences may be attributed to the tasks and the dependent variables. First, Short and Cauraugh's bar moving task differed considerably from the present dial rotation task. Second, Short and Cauraugh compared two rather different grasps whereas a more fine-grained comparison was conducted here. Third, whereas Short and Cauraugh analyzed the positioning accuracy, that is, the performance only at the end of the movement, the overall performance is reflected in the rotation durations analyzed here.

4. General discussion

In Experiment 1 the intention to rotate an object by as little as 5° had a big effect on how the object was grasped. This shows that grasps were adjusted even in anticipation of the tiniest of movements. Additionally, participants excursed their arm stronger when grasping the dial than would be necessary to end the movement in a medial posture. Short clockwise rotations were executed in a range of posture that did not overlap with the range of postures used for counterclockwise rotations. This suggests that other aspects than the postures during the dial rotation determined grasp selections. Experiment 2 examined which grasps were best suited to quickly complete a dial rotation and whether participants selected these grasps. It was found that medial grasp postures tended to result in the fastest rotations, more or less regardless of the direction or extent of the upcoming rotation. Surprisingly, participants twisted their arms stronger during grasping than would be necessary to quickly complete the upcoming object manipulation.

The remainder of the discussion is structured as follows. First, an explanation for the grasp selections in the light of the relationship between grasp selections and rotation speeds will be offered. Second, possible factors that determine how the grasp affected the speed of the dial rotation will be discussed. Third, the current findings are related to previous reasoning on anticipatory grasp selection.

4.1. Grasp selection: control and motor noise

In Experiment 1, participants rotated the arm strongly when grasping a dial that was to be rotated by as little as 5°. Experiment 2 showed that participants thus overshot the grasp that allowed to complete the dial rotation as fast as possible. Moreover, these apparent overshots were observed throughout the entire course of Experiment 1, in which hundreds of dial rotations had to be performed. As participants are generally able to adapt grasp selections to task demands (Seegelke et al., 2013) but adapted their grasp at best slightly in Experiment 1, participants might have actually benefited from investing time and energy to twist their arm seemingly more than necessary.

A possible explanation for the results has been laid out by Trommershäuser, Maloney, and Landy (2003). In their experiment, participants were awarded points if they touched a target. Participants were required to move rapidly, which limited the precision of their movements. Adjacent to one side of the target was a penalty area the touching of which was penalized. Depending on the severity of the penalty, participants aimed at the side of the target opposing the penalty area, rather than at the target's center. This limited the chance of hitting the target, but at the same time, it also reduced the risk of hitting the penalty area. Thus, participants took the variability of their movements into account to choose their aim point. Comparable "safety margins" have been reported for other tasks, including grasping (Schlicht & Schrater, 2007) and object manipulations (Cohen, Biddle, & Rosenbaum, 2010) at moderate speeds, as well as the continuous control of body movements (Adkin, Frank, Carpenter, & Peysar, 2000).

The hitting task parallels the present grasp selection task. As revealed by Experiment 2, rotating the arm too far in the direction of the dial rotation during grasping was strongly penalized by prolonging the dial rotation. By contrast the consequences of rotating the arm too far against the direction of the dial rotation did not affect performance as much. Even though participants were not pressed to grasp the dial rapidly, grasp orientations preceding identical rotations varied from trial to trial. Moreover, as the variability of the forearm orientation at grasping was larger in the grasp-free condition than in the grasp-determined condition (12.5° vs. 6.8°, $t(19) = 4.4$, $p < .001$), it might have been beneficial to aim for more excursed forearm orientation in the grasp-free condition. Such a strategy might reflect the tendency to err on the save side by avoiding relatively costly grasp orientations adjacent to the grasp orientations resulting in the fastest dial rotations. If this reasoning was correct, participants who exhibited more variability in their grasps should select grasps that further overshoot the grasps associated with the fastest dial rotations. Indeed, such a correlation was found, $r = .740$, $t(18) = 4.7$, $p < .001$.[5]

This suggests that grasp selections can be viewed as enhancing the control over the object, given the variability of the arm posture when grasping the object. This is in line with the finding that movement plans are tailored to the own motor variability (Harris & Wolpert, 1998; Meyer et al., 1988; Trommershäuser et al., 2003). Of course, also other factors co-determine grasp selections. For example, in comparable tasks, contextual factors such as the arm posture before grasping, the weight of the object, or the framing of the rotation task have been shown to bias the grasp posture (Herbort & Butz, 2012; Herbort et al., 2014). Likewise, grasp selections are subject to individual preferences (Hughes et al., 2012).

[5] To reflect grasp variability, the standard deviation of the FO_{BEFORE}s were computed for each participant and each rotation angle. As an indicator for how far participants overshot the optimal FO_{BEFORE}, it was computed how much more supine (−135°, −45°, −15°) or prone (15°, 45°, 145°) the FO_{BEFORE}s of grasp-free trials were from the FO_{BEFORE}s associated to the condition that yielded the fastest rotations. The participant-wise averages of these values were entered in the correlation analysis.

4.2. Grasp properties: torque generation and attention

The previous section lined out how the rotation times resulting from different postures might have affected grasp selections. Here, the factors that determined how a grasp posture affects the duration of the dial rotation are discussed. Experiment 2 showed that the fastest dial rotations resulted from grasps close to a medial arm posture. Deviations from that posture in the direction of the dial rotation strongly increased the duration of the rotation whereas deviations against the direction of dial rotation increased durations only slightly (c.f. Fig. 4). It can be speculated that the asymmetry resulted from the combination of the demands of attention and the demands of torque-generation.

First, the finding that medial arm posture at the time of grasping facilitated dial rotation movements in any direction could be explained by attentional factors. When a tool is manipulated, attention is shared between the hand and the effective part of the tool (Collins, Schicke, & Röder, 2008). Such attentional processes might also be involved in object manipulation tasks comparable to the present task (Rosenbaum et al., 1992). Grasping the dial with the index finger at the 0° position (corresponding to a medial grasp), and thus directly between the cursor and the dial axis, might have been the best grasp choice with regard to the attentional processes involved in controlling the object.

Second, stronger pronation torques can be generated in supine postures and vice versa (Darcus, 1951; Matsuoka, Berger, Berglund, & An, 2006; Winters & Kleweno, 1993). Thus, it can be expected that the more the arm is twisted against the direction of the dial rotation during grasping, the faster is the dial rotation.

Both factors could contribute additively to the overall duration of the movement. In the following, the terms "attentional costs" and "torque-related costs" refer to the slowing of the dial rotation due to grasps that are suboptimal to attend the (or cursor) and produce the required torques, respectively. Assume for a moment that attentional costs were lowest for the medial grasp, which resulted from placing the index finger at 0°, and increased the more the grasp deviated from the medial position. Assume further, that the torque-generation costs increased from prone to supine grasps for clockwise rotations and increased from supine to prone grasps for counterclockwise rotations. Given these assumptions, the sum of attentional and torque-generation costs might be lowest for a medial grasp. If the grasp deviates from the medial grasp in the direction of dial rotation, attentional costs and torque-generation costs both increase, resulting in a strong increase in the combined costs. By contrast, if a grasp deviates from the medial grasp against the direction of dial rotation, attentional costs increase while torque-generation torques decrease. Consequently the overall costs might only increase slightly. Thus, the combination of a v-shaped attention cost function and monotonous, direction-dependent torque-generation costs may have caused the asymmetric relationship between grasp and rotation duration.

The above reasoning is supported by another finding. Human supination torques have been shown to depend more on the arm posture than pronation torques (O'Sullivan & Gallwey, 2005; descriptively, this result can also be found in Darcus, 1951; Winters & Kleweno, 1993). Thus, the cost for supinations can be expected to increase stronger from prone to supine postures than the cost for pronations increases from supine to prone postures. Hence, supinations (i.e. clockwise rotations) should suffer especially from choosing the most supine grasp postures, because a stronger increase of torque-generation costs would be added to the attentional costs. On the other hand, when prone grasp postures were used for clockwise rotations, the stronger decrease of torque-generation torque should work more strongly against the increasing attentional costs. This pattern is also reflected in the data (Fig. 4).

In sum, the effect of the grasp on the controllability of the dial can be speculated to result from the combination of torque-generation costs and attentional costs. However, further research is needed to examine which factors make a specific grasp more or less suitable to execute object manipulations.

4.3. Controllability and end-state comfort

Previously, it has been suggested that grasps are selected that enhance precise and fast control over the grasped object by adopting a medial end-state (Rosenbaum et al., 2012). Whereas the present data are compatible with the notion that grasp selections facilitate control (under assumption of compensation for motor noise), Experiment 2 suggested that a medial initial posture rather than end-posture enabled the quickest object manipulations. This conclusion comes with two limitations. First, if participants were required to make larger dial rotations, the costs associated to strongly excursed end-postures or the inability to perform the required rotations with a medial grasp might outweigh the speed benefits determining grasps for smaller rotations. Second, grasp choice might affect movement performance differently for other objects. For example, whereas a pointer or cursor clearly defines the to-be-attended part of the dial, attention might be employed more flexibly when manipulating other objects. For example, in the classic bar transportation task (Rosenbaum et al., 1990) either end of the bar could be attended during the object manipulation and thus, the focus of attention could be flexibly adjusted to the used grasp. Thus, attentional factors might have been a stronger constraint in the present task than in other tasks. Nevertheless, the present experiments suggests that the object manipulation movement and especially its direction may have a greater impact on grasp selection than previously thought.

4.4. Conclusion

The present experiments revealed several main findings. First, it was found that participants strongly adjusted the grasp even in anticipation of tiny object manipulations. This shows that the overarching intentions of a person strongly determine how individual actions, such as grasps, are planned. Second, the grasp selections cannot be explained sufficiently with a posture-based criterion, such as the end-state comfort principle. This became evident as various object manipulations did not share any postures and did not involve medial, comfortable postures. Third, it was found that medial initial grasps resulted in the fastest object manipulations. Nevertheless, participants rotated the forearm against the direction of rotation before grasping the object. These apparent overshoots suggest that grasps were adjusted to the participants' motor variability to enable quick and precise object manipulations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.humov.2015.05.002.

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