LIMITS OF END-STATE PLANNING

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ABSTRACT

The end-state comfort effect is the tendency to use an uncomfortable initial grasp posture for object manipulation if this leads to a comfortable final posture. Many studies have replicated the end-state comfort effect across a range of tasks and conditions. However, these tasks had in common that they involved relatively simple movements, such as picking up a dowel or sliding a pan from one place to another. Here we asked whether the end-state comfort effect extends to more complex tasks. We asked participants to grasp a transparent bowl and move the bowl to an instructed location, positioning it in an instructed orientation. We either found an initial-state comfort effect or equal degrees of comfort for end-grasp and start-grasps depending on task instructions. The end-state comfort effect was not consistently observed. The results suggest that the end-state comfort effect may be restricted to relatively simple grasping movements.

Keywords: Grasping, end-state comfort effect, arm movements

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1 INTRODUCTION

The human motor system affords a great deal of flexibility in the way movements are performed. This flexibility reflects the many degrees of freedom available to the motor system. Selecting particular movements to perform a task when many means are available, is called the degrees of freedom problem (Bernstein, 1967). The degrees of freedom problem appears to be solved in part, at least in the case of grasping movements, by favoring easy-to-control final grasps for tasks requiring great deal of final control. In those cases, people adopt awkward (extreme joint-angle) initial grasps that lead to less awkward (midrange joint-angle) final grasp postures (Rosenbaum et al. 1990, 1992, 1993, 1996).

This effect was first documented by Rosenbaum and colleagues (1990), who asked participants to pick up a dowel placed horizontally on a pair of cradles and then to touch a target on either side of the cradles with a specified end of the dowel. Depending on which side of the dowel had to touch the target, participants grasped the dowel with an overhand or an underhand grip. Experiments showed that the choice of initial grip was determined by the comfort of the final posture. Participants chose an uncomfortable initial (underhand) grip if this led to a comfortable (thumb-up) final posture (Rosenbaum et al. 1990).

Further studies suggested that the end-state comfort effect is found in a broad range of object manipulation tasks. It was found when a dowel had to be moved to shelves placed at different heights (Short and Cauraugh, 1997b), when a dowel had to be rotated (Rosenbaum et al. 1992), when a plunger had to be moved to shelves of different heights (Cohen and Rosenbaum, 2004), and when participants were instructed to slide a pan handle in different directions (Zhang and Rosenbaum, 2008). The effect was also found in children

(Adalbjornsson et al. 2008; Thibault and Toussaint, 2010, Weigelt and Schack, 2010) and in non-human primates (Chapman et al. 2008; Weiss et al. 2007). It has also been studied in different patient groups, including those with cerebral palsy (Steenbergen et al. 2000, 2004) or autism (Van Swieten et al. 2010). End-state comfort planning has been found as well in bimanual coordination (Fischman et al. 2003; Hughes et al. 2011; Weigelt et al. 2006), in whole-body movements (Lam et al. 2006), and in passing objects from one person to another (Gonzalez et al. 2011; Herbort et al. 2012).

The end-state comfort has been taken to support the hypothesis that people plan their movements based on postures, as expressed in a computational model of movement planning (Rosenbaum et al 1995, 2001). In this model, goal postures are selected from a set of stored postures and then subjected to some random variation in a search for a goal posture that best meets the task requirements. The ensuing movement is then planned as a continuous change from the initial posture to the final posture.

Finding evidence for end-state comfort planning across a broad range of tasks would provide strong support for posture-based motion planning. Pursuing this critical test, we asked whether the end-state comfort effect holds in a more complex task than has been previously studied. We asked participants to pick up a transparent plastic bowl and place it at a predefined location in a predefined orientation. This task increases the complexity of previous task in that it involves a continuum of possible grasp positions (rather than the dichotomy between underhand and overhand grasps), and it involves simultaneous translation and rotation as the bowl is moved from one place to another (translation) with its orientation changing from the first place to the second (rotation).

Whereas several studies have used a continuum of possible grasp positions (Cohen & Rosenbaum, 2004; Zhang & Rosenbaum, 2008), just one earlier study appears to have combined a continuum of grasp positions with simultaneous translation and rotation (Cohen & Rosenbaum, 2011).

If participants consistently used an end-state comfort strategy, we would expect them, by definition, to grasp the bowl in such a way that that they would adopt comfortable posture at the ends of the bowl displacements. To test this prediction, we conducted six experiments, first to replicate the findings under a range of conditions, and second, to examine possible factors involved in the effect, such as planning time and grasp flexibility. To anticipate the main result, we found evidence for initial- rather than end-state comfort in the first experiment, but then, in the subsequent experiments, we found no consistent preference either for initial- or end-state comfort. In the General Discussion section we consider the theoretical implications of this finding.

2 GENERAL METHODS

The experiments described here were conducted in two stages. The first set of experiments (Experiments 1, 3 and 6 below) was conducted at Penn State University, where four possible bowl positions (rings to place the bowl in) were used. The analysis of the grasps in these experiments was conducted by video-recording the movements and then by analyzing the grasp positions on a frame-by-frame basis. The second set of experiments (Experiments 2, 4 and 5 below) was conducted at the University of Aberdeen, where we used only three possible bowl positions (restricting the number of possible movement combinations, allowing for the inclusion of rotation-only and lift-only trials). The bowl and hand movements in this second set of experiments were recorded using Mantra software (Mathot and Theeuwes, 2011), controlled by OpenSesame (Mathot et al. 2012) and analyzed using a Matlab script to determine the grasp position on the rim of the bowl.

2.1 Participants

Participants were undergraduate students at Penn State University and at the University of Aberdeen. Their ages ranged from 18 to 25 years and included approximately equal numbers of males and females. All but one participant was right-handed. Before taking part, participants provided written consent. In return for their participation they were awarded course credit.

2.2 Apparatus

As shown in Figures 1A and 1C, a transparent plastic bowl was used. The bowl used at Penn State measured 14 cm in height, had a top rim with a diameter of 22 cm, and a bottom rim with a diameter of 11 cm. To indicate the bowl's direction, a wooden stick was attached 1.5 cm from the bottom of the bowl, measuring 11 cm in length, and 1 cm in diameter. The bowl used at Aberdeen was 10.5 cm in height, had a top rim diameter of 23 cm, with a red transparent plastic pointer attached to the bottom, extending the upper rim by 12 cm.

-Figure 1 about here-

The Penn State setup consisted of a table top with four foam rings (outer diameter = 19 cm, inner diameter = 14 cm), each containing three gaps 1.5 cm wide (Figures 1A and 1B), placed in a semi-circular arrangement around the home position (i.e., the start position for every trial). Gaps in the Penn State setup were placed such that the first gap, labeled 'A,' was located on an imaginary line between the center of the home position and the center of the ring. The other two gaps, labeled 'B' and 'C,' were at 120 degree angular deviations from the first gap.

The Aberdeen setup consisted of a table top with three rings placed on a similar circular arrangement around the home position (Figure 1D). Rings were created from plastic plates (diameter = 17 cm), by cutting out three gaps (each approximately 3cm in width), placed such that movements from gap 'A' (or 'B' or 'C', respectively) from one ring to another mostly involved a translation of the bowl in the sense that a larger proportion of the possible translation distance was covered by these movements than was the possible rotation angle.

In the Penn State setup, the participants' arm movements were videotaped using a JVC digital video camera (model GRDVL805U) positioned on a tripod atop a cabinet looking down on the setup (Figures 1A and 1B for images). A list of the target ring and gap for each trial was printed on paper and read out by the experimenter.

In the Aberdeen setup, the target for the upcoming task was presented on a computer screen (not visible to the participant) and was read out by the experimenter. Movements were recorded by means of the software package Mantra (Mathot and Theeuwes, 2011), using the images from a webcam (320x240 pixels resolution), pointing at the table from a shelf positioned above and slightly to the left of the table (see Figure 1D for an image).

2.3 Design

In both the Penn State and Aberdeen setup, a randomized list was created for each participant. Each participant's list had all possible start and end combinations (of ring and gap), such that on each trial the start combination was identical to the end combination of the previous trial. This sometimes required the insertion of a few filler items towards the end of the list to ensure that start and end combinations across successive trials matched up.

In the Penn State setup, we only included movements that involved movement of the bowl from one ring to another. In the Aberdeen setup, we also included trials with the same ring ('rotate only' trials) and trials with identical start and end combinations ('lift' trials). Participants typically took part in around 100 trials.

2.4 Procedure

In the Penn State setup, participants were asked to stand in front of the table with the bowl and the rings, and to keep as close to the table as possible to prevent moving extensively while performing the task. In the Aberdeen setup, participants were seated at the table, in part to test whether this change in posture would affect the results. In both setups, we asked participants to place their hands, between trials, at a designated start position on the table (near the body).

In most of the experiments, we provided the instruction where to move the bowl by means of a number-letter combination. For example, when the experimenter read out '2B,' this meant the bowl was supposed to be placed in ring 2 with the pointer in the gap indicated by the letter B. Unless otherwise indicated, participants were asked to move the bowl with the right hand, placing the thumb inside the bowl's rim. No instructions were given about movement speed. Participants were familiarized with the task in a few practice trials.

Throughout the experiment, the experimenter monitored the participants' performance and provided corrective comments if the participants used a grasp not permitted by the instructions. Participants were offered the opportunity to take a break (at one third and two thirds of the way through the session at Penn State and at any time at Aberdeen), but participants rarely did so. The experiment, including instruction and debriefing, usually took 20 to 25 minutes.

2.5 Data Analysis

In the analysis of the Penn State experiments (Experiments 1, 3 and 6) the digital video recordings were processed manually. This involved extracting the critical video frames (start and end of each movement) and identifying the position of the thumb on the bowl's rim in each such frame by clicking on the thumb's position in the image using a custom-built Matlab script (illustrated in Figure 1A). In the analysis of the Aberdeen experiments (Experiments 2, 4 and 5), we used the output of Mantra which coded the start and end of each movement, and we computed the grasp position on the rim from the coordinates of the center of the bowl and the position of the hand (Figure 1E). The thumb or hand position was coded as an angle in both types of analysis, with zero degrees coding a grasp position on the right-most position on the rim, negative angles as positions at the lower part of the rim (closer to the participant) and positive angles coding for grasps of the upper part of the rim (away from the participant). Occasionally, participants made grasp corrections. In those instances, we used the grasp position with which they ultimately took hold of the bowl. We found that Mantra was fairly accurate at tracking the position of the hand and the bowl, but approximately 30% of the trials had to be removed because either the start or the end grasp position could not be estimated due to occlusion of the colored patch on the glove worn by the participant (see below) or the bowl.

3 EXPERIMENT 1

Experiment 1 provided the baseline measure of whether the end-state comfort effect applies in this task context.

3.1 Method

Seven right-handed participants took part in Experiment 1, which was conducted at Penn State University. Each movement involved the transfer of the bowl from one ring to another. Four target positions (rings) with each of three target orientations (gaps) were used. The instruction concerning the target position was provided verbally (e.g., '1A', for ring 1 and gap 'A'). As already mentioned, movements were recorded using a video camera, and grasp positions were determined by clicking on the thumb position in the relevant video frames (Figure 1A).

To evaluate the comfort of the grasps, we asked 16 additional participants to compare the comfort of seven randomly selected pairs of grasps (start and end grasps) of each of the original seven participants, indicating which grasp appeared more comfortable for each pair. The grasps were seen rather than adopted by the raters, though no attempt was made to prevent the raters from mimicking the postures they saw. The postures that were shown were from frozen video frames, showing a start and an end grasp side by side (Figure 1C). The position (left or right) of each grasp in a pair was randomly chosen.

3.2 Results and Discussion

Figure 2 provides an overview of the results of Experiment 1. As a first step in the data analysis, we examined the distributions of initial and final grasp positions on the rim. These are shown in Figure 2A. Grasps on the right side of the rim (as seen from the participant) are shown as a grasp position equal to zero, whereas grasps at the bottom part of the rim are shown as negative grasp positions, and grasps at the top part are shown as positive numbers. The histograms in Figure 2A suggest that most grasps were made in the lower right quadrant of the rim.

- Figure 2 about here -

In a second step of the analysis, we defined comfort zones separately for each of the ring positions. We did this across participants, as insufficient data were available to estimate the comfort zone for each participant individually. On the basis of the histograms, shown as dotted lines in Figure 2A and red zones superimposed on a graphical representation of the experiment's layout in Figure 2B, the comfort zones were defined as the median grasp position plus or minus 45 degrees.[1] We determined the percentage of trials in which participants started or ended their grasp inside these comfort zones, as shown in Figure 2C, when averaged across participants, with the error bars showing the standard error of the mean. The data plot suggests that initial grasps were more often comfortable than final grasp positions. This inference was confirmed by a Wilcoxon signed rank test for pairwise comparisons ($p=0.0078$), suggesting an initial state comfort effect rather than an end-state comfort effect.

In a second step, we examined whether a more continuous measure based on the histograms would yield the same outcome, which also provides a method to deal with the

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[1] This was an arbitrary chosen value; we repeated the analysis with other values, and found a similar pattern of results regarding the proportions of start-only and end-only comfort zone grasps. This was also the case for different ways of defining the comfort zone, for example, using the full-width-at-half-maximum of the histograms.

possibility of multiple comfort zones for each ring. To this end, we estimated the frequency of grasps along the rim in bins of 20 degrees (balancing between obtaining reliable frequency estimates and using small enough bin sizes), and used these frequencies to compute an average measure of comfort for initial and end grasps in the experiment ('weighted frequency'), as shown in Figure 2D. Also this measure yielded a higher comfort estimate for start than for end grasps ($p=0.0078$, Wilcoxon signed rank test).

To further analyze this possible initial-state comfort effect, we scrutinized the data from the rating task, in which participants were asked to indicate, for a random selection of pairs of initial and final grasp positions shown as still-shots from the movie clips, which grasp seemed comfortable. The results are shown in Figure 2E. The figure depicts the proportion of trials in which the initial grasp, the final grasp, or neither of the two grasps was considered to be more comfortable, averaged over participants. Initial grasps were rated more comfortable when comparing initial and final grasps pairwise for each participant, $t(6)=2.60$, $p=0.041$, though this difference just failed to reach significance when compared with the slightly more conservative signed rank test, $p= 0.0625$.

The ratings were used to determine which grasps were considered to be comfortable by counting the number of times a grasp in the photograph was chosen as more comfortable, for a range of grasp positions. The results of this analysis are presented in Figure 2F, showing for each ring position and for one of the eight cardinal grasp directions (zones of 45 degrees around these directions were defined for the counting) the proportion of trials in which the grasp was chosen to be more comfortable. Higher values in this plot correspond to higher comfort. We used these numbers to estimate the comfort of initial and final grasps, taking a weighted average of the nearest two grasp comfort estimates. A comparison of these estimates confirmed the results of the earlier analyses of Experiment 1, showing higher comfort for initial grasps than for final grasps, p=0.016, in a signed rank test, as shown Figure 2G.

We next checked to see whether grasp positions were influenced by previous grasps, as has been reported in previous studies (e.g., Cohen and Rosenbaum, 2004). For this purpose, we plotted the final grasp on the current trial against the initial grasp on the next trial (participants going back to where they ended) and the initial grasp on the current trial against the initial grasp on the next trial (participants repeating a previous grasp), as shown in Figure 2H. A small but consistent correlation turned up between end grasps and initial grasps on sequential trials (average correlation = 0.28, p=0.0078). However, no correlation was found for initial grasps between trials (average correlation = -0.072, p=0.055, signed rank test).

The main result of Experiment 1, then, was that participants adopted an initial-state comfort strategy when picking up a bowl to place it at a different location with some specified orientation. This conclusion was supported both when the data were analyzed using a comfort zone analysis and when estimating the comfort of grasps on the basis of ratings from an independent group of participants, providing converging evidence for initial-state rather than end-state comfort.

4 EXPERIMENT 2

The finding of the first experiment was clearly at odds with earlier observations of end-state comfort planning in tasks that both involved rotation and translation (Zhang and Rosenbaum, 2008; Cohen and Rosenbaum, 2011). To explore the reason for this change of outcome, in the second experiment, we used a different method of measuring grasp positions and of estimating both comfort zones and comfort ratings. Our aim was to check whether the different outcome was an artifact of some aspect of the data-analysis procedure used for the first experiment.

In the analysis of the data for Experiment 1 we had to make a few assumptions about how to classify grasps as comfortable or uncomfortable. The comfort zones that we used may have been problematic because the classification was based on all trials, both comfortable and uncomfortable. Ratings also suggested that the comfort zones were not restricted to one segment of the bowl.

In Experiment 2, we addressed these issues by adding 'lift' trials. In these trials participants were simply asked to lift the bowl and place it back in its original position with its original orientation. These grasps presumably involved less complex movement planning than did lift-followed-by-transport-and-place movements. The lift-and-then-lower movements had the same initial and final postures, so they were likely to result in the most comfortable grasp and could, therefore, be used as a baseline. Experiment 2 also included 'rotation only' trials in which participants were asked to rotate the bowl, staying with the same ring. This type of movement planning might be seen as less complex than the full lift-followed-by-transport-and-place movements used in Experiment 1. If movement complexity compromised end-state comfort in Experiment 1, it might have been more prominent in Experiment 2.

Besides the method to estimate the 'comfort zone' in Experiment 1, the method to compute comfort ratings for each grasp position may have also been suboptimal. First, the method used photographs of grasps, which may not have provided adequate perceptual input to participants to estimate comfort. Better ratings might be obtained if ratings were made when participants took hold of the bowl itself. Second, the computation involved comparisons between initial grasps and end grasps, and the derived comfort values might have been biased or misleading in some way. Because no previous study has addressed whether comfort ratings are similar for viewed grasps of objects as opposed to actual grasps of objects, at least as far as we know, we asked two additional groups of participants to perform both types of rating tasks (rating photographs and rating performed grasps), so we could compare the two types of ratings.

4.1 Method

Ten participants took part in the main task of Experiment 2 (grasp-and-lift or grasp-and-move), which was carried out at the University of Aberdeen. Participants were seated at a table containing just three rings (Figure 1D), so there were fewer start-end and ring-gap combinations than in Experiment 1. This reduction of the number of rings from 4 (Experiment 1) to 3 (Experiment 2) allowed inclusion of all possible start-end, rotation-only, and lift-only trials; otherwise the session would have been too long and taxing for the participants. The instructions were again given verbally.

The movements of the hand and bowl were measured using Mantra (Mathot and Theeuwes, 2011). A blue patch on the inside of the bowl and a green patch attached to a glove, with the finger sections removed, were used to identify the points of interest. These were characterized with a custom-built Matlab program, yielding images like the one shown in Figure 1E. Trials in which the signal of the hand or bowl went missing were removed from the analysis. This led to the exclusion of, on average, around 30% of the trials. The proportion of removed trials was slightly higher in lift and rotation trials (exclusion rates of 35%, 38% and 24% for lift, rotation, and move trials respectively), possibly because these trials did not involve large and distinct movements of the bowl. Because of the relatively large number of trials performed by each participant (around 100 each), sufficient data was left to obtain good estimates of initial and end thumb positions (see also the Discussion) for each of the bowl positions. Estimates of the comfort zones and weighted frequencies based on the "lift" trials, however, needed to be based on data across participants (as in Experiment 1) to obtain a reliable estimate of the frequencies of the grasp positions.

The comfort of the grasps was assessed by asking 32 additional participants (1) to rate the comfort of the photographed grasps along the rim at the cardinal directions (0, 45, 90, etc. degrees) for each of the three rings on a 1-to-5 scale, and (2) to rate the comfort of these grasps when performed themselves (just taking hold of the bowl), also on a 1-to-5 scale. Half of the participants first performed the visual task, whereas the other half first provided the grasp-based-ratings. Because the analysis of these ratings showed a small, but significant difference between the different types of ratings, but not of the order of the tasks, we used the average grasp-ratings across all participants for the subsequent analysis. To compute comfort of the grasps in the main bowl-moving task, we computed an extrapolated comfort rating for each grasp position and for each of the positions (rings), using a weighted average of the rating of the thumb position left and right of the grasp position.

4.2 Results and Discussion

The results of Experiment 2 are summarized in Figure 3. Comfort zones were computed on the basis of the trials in which participants lifted the bowl to place it back in the same ring and with the pointer in the same gap (Figure 3A). Because the distribution of grasp positions in this condition approached a normal distribution, we could use the mean and (4 times) the standard deviation to compute the comfort zones[2]. A comparison of the number of trials with the start and end grasp inside the comfort zone revealed similar proportions of trials with only the start (initial-state comfort) or only the end (end-state comfort) grasp in the comfort zone on combined translation and rotation trials (Figure 3B; p=0.65, signed rank test). For rotation-only trials, the data plot suggests a slight tendency towards an end-state comfort effect, but the significance of this tendency was not confirmed by the statistical test (p=0.71, signed rank test).

The continuous measure based on grasp frequencies yielded a slightly different pattern of results, as shown in Figure 3C, without evidence for end-state comfort. For translation-and-rotation trials no differences in weighted frequencies of start and end grasps was found (p=0.77, signed rank test). For rotation-only trials, evidence for initial state comfort was obtained (p=0.0059, signed rank test).

-Figure 3 about here-

Average comfort ratings are shown in the form of polar plots in Figure 3E, comparing the effects of presentation order (visual or grasp ('propioceptive')-condition first) and the type of ratings (visual or grasp-based). A mixed factor ANOVA testing the effects of presentation order (between subjects), ring location (within subjects), angle (within subjects) and type of rating (within subjects) revealed a significant three-way interaction between the three within-subject factors ($F(14,420)=3.86$, $p<0.001$). When considered for each ring

2 As for Experiment 1, we tested various sizes of the comfort-zone, which led to similar results regarding the relative comfortable start-only and end-only grasp frequencies.

separately, ring 1 showed a significant interaction between type of rating and angle ($p=0.012$). For ring 2 significant main effects were found for angle and type of rating (both p-values<0.001), but no interaction. For ring 3 another interaction between type of rating and angle was found ($p<0.001$). These effects did not interact with the order in which participants performed the task, nor was there a main effect of the order of the task. These data suggest that ratings depend on the task (although not to a huge extend, see Figure 3C), but not the order of the task. For this reason and because the grasp-based are more likely to reflect perceived comfort during the grasp-and-move task, we used the proprioceptive ratings across all participants to obtain an estimate of initial and end-comfort during the grasp-and-move task.

Using these values, the pattern in Figure 3D is found, revealing no end-state or initial state comfort effect ($F(1,9)<1$) and no effect of type of movement ($F(1,9)<1$), consistent with the comfort-zone ratings, and most of the weighted frequency results. Inter-trial comparisons showed a small, but systematic correlation between previous end grasps and current initial grasps ($r=0.30$, $p=0.0020$, signed rank test). The correlation between previous initial and current initial grasp positions did not reach significance ($r=0.13$, $p=0.065$).

Summing up the results of the second experiment, whereas Experiment 1 yielded an initial-state comfort effect, Experiment 2 yielded evidence for initial-state comfort only for rotation trials when a weighted frequency comfort measure was used. Irrespective of whether the bowl task led to initial-state comfort or not, however, the results do not support the end-state comfort effect, in contrast to the many earlier findings supporting the effect, as summarized in Rosenbaum et al. (2012). In the next three experiments, we explored several possible reasons why this may have been the case.

5 EXPERIMENT 3

Because Experiments 1 and 2 did not provide evidence for end-state comfort planning in the bowl grasping task, we asked in Experiment 3 whether this outcome may have been an artifact of the instructions in the first two experiments. The hypothesis was that hearing letter combinations such as '1A' may have caused participants to code the task in a way that, for whatever reason, tempered the weight that otherwise would have been given to end-state comfort.

To test this possibility, we changed the instruction in Experiment 3 by refraining from giving verbal instructions in each trial. Instead, the experimenter placed a wooden block near the target gap, as shown in Figure 1B. This method of signaling the target destination ensured that participants saw the target gap before picking up the bowl and moving it.

5.1 Methods

Nine participants took part in the experiment, which was conducted at Penn State University. A piece of wood (10 cm long, 6 cm wide, 1.5 cm thick), covered with green tape (allowing it to be visible in the video recordings) was used to instruct participants where to move (Figure 1B). Four ring positions, each with three gaps were used. Only trials with movements from one ring to another were included. Participants stood next to the table with the setup.

5.2 Results and Discussion

Figure 4 summarizes the results of Experiment 3, using the methods from Experiment 1 to estimate the number of grasps inside the 'comfort zone', the comfort based on the frequency of grasps (using a bin-width of 20 degrees) and the comfort based on the ratings from Experiment 1. All three methods suggest that participants neither adopted an initial-state comfort effect nor an end-state comfort effect. Proportions of grasps inside the comfort zone (Figure 4A), defined as the median grasp position across all conditions for each ring plus or minus 45 degrees, were no different for start grasps and end grasps ($p=0.91$, signed-rank test). Estimated comfort based on the frequencies of lift-grasp angles was not significantly different across start and end grasps (Figure 4C, $p=0.25$, signed-rank test). Finally, estimated comfort (Figure 4C) was not different for start and end grasps ($p=0.25$, signed-rank test).

Inter-trial comparisons are in line with Experiments 1 and 2. A comparison of subsequent grasps showed a small but systematic correlation between the final grasp position on the previous trial and the initial grasp position on the current trial ($r=0.30$, $p=0.0039$). No such correlation was found between the initial grasp on the previous trial and the initial grasp on the current trial ($r=0.030$, $p=0.50$).

-Figure 4 about here-

When compared to Experiment 1, these results may suggest that participants moved towards an end-state comfort effect due to the visual instruction of target location and orientation. However, a comparison with the results of Experiment 2 suggests that the initial-state comfort effect in Experiment 1 may have been due to the specific sample of participants, which, considering the individual data (and ratings of their grasps), seemed to contain a few participants showing a strong tendency towards initial state comfort.

6 EXPERIMENT 4

Experiment 3 showed that the lack of full information about the target position (its location and orientation) could not explain the absence of the end-state comfort effect. It may have been, however, that participants simply acted in a more impulsive way in this series of experiments than they did in previous experiments in which the end-state comfort effect was observed. Subtle aspects of the way the present experiments were conducted could have possibly led the participants tested here to respond before they had planned as fully as they might have had they been given, or force to take, more time. To address this possibility, in Experiment 4, we introduced a delay between the presentation of the target and the signal to start the grasping movement.

6.1 Method

Ten participants took part in the experiment, which was conducted at Aberdeen University. Participants performed the bowl-grasping task in two sessions, separated by at least one week to avoid memory effects. Half of the participants first performed the task without a delay, whereas the other half first performed the task with the delay. The no-delay task was identical to Experiment 2. The delay task, by contrast, had participants wait for 2 seconds after receiving the instruction where to move, after which a beep sounded from the computer to indicate they could start their movement. In the delay condition, we found that a very large number of trials (90%) had to be excluded from the lift condition, because of missing samples. Because of this, we used the lift trials in the no-delay condition to estimate the 'comfort zones' for both the delay and the no-delay conditions.

6.2 Results and Discussion

The percentage of trials with a grasp inside the comfort zone, based on the distribution of the grasp sites in the lift condition in the no-delay condition, is shown in Figure 5A and Figure 5B for the no-delay and delay conditions, respectively. To evaluate the influence of delay on these percentages for the combined translation and rotation trials, we conducted a repeated measures ANOVA to test the effects of the delay and the difference in percentages between the start and end grasps. The ANOVA yielded a main effect of delay ($F(1,9)=7.02$, $p=0.026$), but no main effect of grasp type (start versus end: $F(1,9)=0.73$, $p=0.42$) and no interaction between the two factors ($F(1,9)=0.021$, $p=0.66$). As seen in Figures 5A and 5B, the main effect of delay was an increased numbers of grasps with both the start and end grasp in the comfort zone ($p=0.037$, signed-rank test). For the rotation-only trials, there was no effect of the delay ($F(1,9)=3.03$, $p=0.10$), no difference between start and end grasp ($F(1,9)=2.54$, $p=0.12$), and no interaction between the two factors ($F(1,9)=1.39$; $p=0.31$).

For the weighted frequency measure, the pattern of results in Figures 5C and 5D is obtained. For translation plus rotation trials, a significant interaction between delay and grasp type is found ($F(1,9)=5.50$, $p=0.044$). In the no-delay condition, evidence for an end-state comfort effect for translation plus rotation trials is found ($p=0.014$, signed rank test). As in Experiment 2, the rotation trials resulted in an initial state comfort effect on this measure ($p=0.0039$, signed rank test). With a delay, no evidence for end-state comfort is found ($p=0.49$) for translation plus rotation trials, but there is evidence for initial state comfort for rotation only trials ($p=0.0078$).

-Figure 5 about here-

Figures 5E and 5F show the estimated comfort of start and end grasps, based on the grasp-based comfort ratings from Experiment 2. For the combined translation and rotation trials, a repeated measures ANOVA revealed no effects of delay (F(1,9)=4.58, p=0.061), no difference between start and end comfort (F(1,9)=0.40, p=0.54), and no interaction between these factors (F(1,9)=0.41, p=0.54). For rotation-only trials, the same pattern of results was found, with no effect of delay, F(1,9)=2.60, p=0.14, no significant difference between start and end grasps (F(1,9)=0.2.18, p=0.17), and no interaction between the two factors (F(1,9)=0.60, p=0.46). As in the previous experiments, a small but systematic correlation was found between final grasps on the previous trial and initial grasps on the next trial (r=0.16, p=0.0098 for no-delay trials, and r=0.16, p=0.0039 for delay trials). No such correlation was found between initial grasps of successive trials (r=0.033, p=0.38 for no-delay trials, and r=-0.066, p=0.28 for delay trials).

Because Experiment 4 was conducted in two sessions and the order of the delay conditions was counter-balanced across participants, we could also examine the influence of practice on the end state comfort effect. If participants improve with practice, we would expect them to show more end-state comfort planning in the second session.

Data bearing on this expectation are shown in Figure 6, which shows the effects of the session (averaged across the delay conditions) on the percentage of grasps in the comfort zone (Figure 6A), the weighted grasp frequency measure (Figure 6B), and the estimated comfort based on the grasp ratings (Figure 6C). The most obvious effects of practice were found on the percentage of grasps in the comfort zone and the weighted grasp frequencies for rotation-only movements. The tendency towards an end-state comfort effect (p=0.13, signed-rank test) turned into an initial-state comfort effect (p=0.016), for the in-comfort-zone measure. A similar trend was found for the weighted grasp frequencies (1st session: p=0.30, 2nd session: p=0.023). None of the other comparisons yielded evidence for either an initial-state or end-state comfort effect across sessions (translation + rotation in-comfort percentages and estimated comfort ratings), or an effect of session.

-Figure 6 about here-

The effects of the delay in Experiment 4 were unexpected, because the only indication for end-state comfort was found without a delay when a weighted lift-grasp frequency was used to estimate comfort. With the delay no evidence for end-state comfort was obtained, suggesting that the absence of the end-state comfort effect in previous experiments was not due to participants taking insufficient time to plan their movements.

7 EXERIMENT 5

In all of the experiments reported so far, participants were asked to grasp the bowl by placing their thumb inside the bowl. Whether this restriction on the grasp influenced people's grasps was investigated in Experiment 5. Here we let participants choose their grasp (thumb inside or fingers inside). If the absence of the end-state comfort in the previous experiments was due to the requirement to put the thumb inside the bowl, the effect might return if this requirement were removed.

7.1 Method

Ten participants took part in the experiment, which was conducted at the University of Aberdeen. Participants performed the same task as in Experiment 2, but were no longer instructed about how to grasp the bowl and therefore could choose whether to place their thumb or their fingers inside the bowl when grasping the object.

7.2 Results

Figure 7 provided an overview of the results of Experiment 5. Four participants preferred thumb-inside grasps, four participants almost always grasped the bowl with their fingers inside the bowl, and two participants alternated between fingers inside and thumb inside (Figure 7A). Across conditions (translation + rotation versus rotation only versus lift trials), there was no bias towards either type of grasp (Figure 7B; $F(2,11.9)=0.64$, $p=0.48$; repeated measures ANOVA, Greenhouse-Geisser corrected).

-Figure 7 about here-

Figures 7C and 7D show that the extra flexibility about to how to grasp the bowl (thumb or fingers inside) did not lead to the introduction of an end-state comfort effect. Equal percentages of start and end grasps ended inside the 'comfort zone' (translation + rotation trials: $p=0.49$, signed-rank test; rotation only: $p=0.48$). Similar results are obtained when the weighted grasp frequency on lift-trials is used (Figure 7D; translation + rotation trials: $p=0.92$, rotation only: $p=1.0$, signed-rank tests). Because the same thumb positions on the rim may not correspond to the same comfort with the thumb placed inside or outside, we do not report the converted comfort ratings for Experiment 5.

As in previous experiments, a small but significant correlation was found between end-grasps on previous trials and start-grasps on current trials ($r=0.22$, $p=0.014$), but not between start-grasps on successive trials ($r=0.11$, $p=0.13$).

8 EXPERIMENT 6

In the sixth and final experiment, we sought to determine whether the specificity of the tasks in the previous experiments accounted for the absence of the end-state comfort effect. In Experiment 6, we asked participants to move the bowl to a target ring and place the pointer in one of the three gaps, but the participants were not told which gap to choose. They were thus free to choose whichever gap they wished. If the absence of the end-state comfort effect was due to the constraint to bring the bowl to a specific orientation, the effect might return if this requirement were lifted.

8.1 Method

Eight participants took part in Experiment 6, which was conducted at Penn State University. The experiment was identical to Experiment 1, except that only a target ring, but no target gap was announced by the experimenter. Participants were still required to place the pointer of the bowl into one of the three gaps, but they were free to choose the gap they used.

8.2 Results and Discussion

Analysis of the gap selections showed that participants chose gaps that involved small bowl rotations (Figure 8A). These choices led to a high percentage of trials with both the start and end grasp in the 'comfort zone' (Figure 8B), defined on the basis of the distribution of all grasps, which was higher than in the other two experiments in the same set (compared to Experiment 1: rank-sum=42, $p=0.0047$; compared to Experiment 3: rank-sum=100, $p= 0.0055$). The remaining grasps did not show significantly more start-only than end-only comfort grasps ($p=0.15$, signed rank test), and the weighted frequency estimate was no different for start and end grasps (Figure 8C; p=1.0, signed rank test). Estimated comfort was also high (Figure 8D, start-comfort was higher than in Experiment 1: rank-sum=46, p=0.021 and Experiment 3: rank-sum=41, p=0.0028, as well as end-comfort, Experiment 1: rank-sum=39, p= 0.0011, however not in Experiment 3: rank-sum=57, p=0.28), but no evidence for end-state comfort was found (p= 0.15, signed rank test).

-Figure 8 about here-

These results, which are similar to those presented in another study (Elsinger and Rosenbaum, 2003) suggest that in the other experiments reported here, participants attempted some form of anticipatory control, as initial grasps for the simpler task in Experiment 6 were more comfortable than in the more complex tasks of Experiment 1 and 3. However, the results of the present experiments also suggest that participants in Experiments 1 and 3 were not very successful at achieving end-state comfort, since we found that end-comfort was often higher in the simpler task of Experiment 6 than in the more complex task of Experiments 1 and 3.

9 GENERAL DISCUSSION

Several studies have suggested that participants, when grasping an object, take hold of the object to ensure a final comfortable posture (Cohen and Rosenbaum, 2004, 2011; Rosenbaum et al. 1990, 1992, 1993, 1996; Short and Cauraugh, 1997, 1999; Zhang and Rosenbaum, 2008). We tried to extend this finding to a somewhat more complex task, involving picking up and moving a bowl to an instructed location and orientation. Our six experiments that examined this task did not yield an end-state comfort effect, suggesting that the effect may be restricted to simpler tasks.

We ran our experiments with ten or fewer participants each, so one may wonder whether our experiments had the statistical power to detect a preference for comfortable end-grasps over comfortable start-grasps. On the basis of previous research, large effect sizes, and therefore high statistical power with a limited number of participants, were expected. For example, Rosenbaum et al. (1990) found that all participants (n=11) in their study used end-state comfort when grasping a dowel. Similarly, Rosenbaum et al. (1992) found that close to 90% of their participants used end-state comfort when rotating a dial. Our observations of initial state comfort (Experiment 1; rotation-only trials in some instances in the other experiments) or equal initial and end-state comfort without a hint of an effect towards end-state comfort (remaining experiments) strongly suggests that something else was taking place in our task.

Such an interpretation is supported by the fact that combining data across experiments, for example the comfort-zone-rates found in Experiment 2, with the rates of participants in Experiment 4 who started without a delay (resulting in a total n=15), or Experiments 2, 4, and 5 (ignoring the order of the blocks or whether grasps were with the thumb inside or not, resulting in a total of 30 participants), did not lead to significant end-state comfort (p=0.81 for the first comparison, and p=0.46, for the second). These observations agree with a more subjective impression while watching the video recordings of the movements that participants. Participants at times ended in very awkward end postures, even to the point that they sometimes had to place the bowl with the pointer outside the gap and then re-grasp the bowl at a different location on the rim to put the pointer inside the gap. Awkward end postures were not infrequent and could be seen throughout the experimental session. This outcome suggests that the absence of an end-state comfort effect may have been related to an inability to fully plan for the end.

We can return, then, to the possible explanations we already considered for the lack of the end-state comfort effect in the present bowl-grasping task. First, we showed that the absence of the effect was not due to participants not looking where they were going before initiating the grasping movement. When the instruction changed from a verbal instruction (Experiments 1 and 2) to a visual instruction (Experiment 3), the end-state comfort effect did not materialize. Second, the absence of the effect was unlikely to have been due to insufficient planning time. When participants were forced to wait 2 seconds after receiving the instruction where to move the bowl before taking hold of the object, the end-state comfort effect was not restored (Experiment 4). Third, the lack of the end-state comfort effect was not due to restriction of grasping the bowl with the thumb inside the ring. When participants were allowed to take hold of the bowl in either a thumb-inside or fingers-inside grasp, this did not lead to restoration (or first manifestation) of the end-state comfort effect in this context (Experiment 5). Participants appeared to attempt to achieve end-state comfort, as initial grasps were more uncomfortable when large rotations were involved (Experiments 1-5) than when such large rotations could be avoided (Experiment 6).

There are a few alternative explanations of why the effect did not occur. First, one may argue that our task did not require sufficient precision at the end of the movement for the end-state comfort effect to occur. Effects of end-state precision were found by Short and Cauraugh (1999), who compared end-state comfort planning for small (high precision) and large (low precision) targets, and found that end-state comfort was more consistently observed for high precision targets (see also, Rosenbaum et al. 2006). Similarly, Rosenbaum, van Heugten and Caldwell (1996) found an effect of the precision instruction on how participants grasped a handle in order to rotate it. We did not explicitly test for end precision here, for example by using small and large gaps in our rings, although our gaps were smaller in Experiments 1, 3, and 6 than in the remaining experiments. Nonetheless, we think it is unlikely that end precision was an important factor in our experiment. The gaps in our rings were generally small (particularly in Experiments 1, 3 and 6) and therefore relatively precise aiming was needed. Furthermore, participants were at times found to correct their movements at the end of the movement to ensure that the point fell into the gap. In a similar task, which involved sliding rather than picking up a bowl (Zhang and Rosenbaum, 2008) larger targets were used, and this task led to an end-state comfort effect, suggesting that the size of our targets was not a factor.

Related to the precision argument, it may be argued that our task placed equally strong precision requirements on both the start and the end of the movement. Participants might have tried to maximize overall control during the task, as in another recent study (Künzell et al. in press), and this could explain why we found no evidence for either initial-comfort or end-comfort.

Contrary to this interpretation, however, if participants adopted such an overall control strategy, we would have expected most grasps to both start and end comfortably, or both start and end uncomfortably, but not to find many grasps that started comfortably but ended uncomfortably or the reverse. We found such a pattern with mostly comfortable start and end grasps for Experiment 6, in which participants were allowed to choose the gap they used for the pointer, but this pattern was not found in the other experiments. This makes an explanation in terms of overall control unlikely.[3]

A possible second reason why we did not find evidence of the end-state comfort effect might be related to ecological validity. Steenbergen and colleagues (2004) found that when participants were asked to pick up a dowel and point with it on a table, this led to fewer observations of end-state comfort planning than when a pen was used, leaving marks on the paper. Our participants were not very familiar with the task of picking up a bowl and placing it in a designated orientation, as this is not a very common task in daily life. Possibly, people may pick up cups and place them in an orientation such that a second person can pick it up, but this often involves the use of a handle. In our task, by contrast, participants were asked to use the rim to pick up the bowl.

A counterargument can be given to the one concerning ecological validity, however. Many studies have found end-state comfort planning for other, less common tasks, such as picking up a dowel to use it to touch a target (Rosenbaum et al. 1990) or sliding a bowl's pointer into a cup (Zhang and Rosenbaum, 2008).[4]

Grasps by our participants were influenced by where they ended their movement on the previous trial. Such inter-trial effects have been reported before (Cohen and Rosenbaum, 2004, 2011; Short and Cauraugh, 1997; Weigelt et al. 2009). For example, Cohen and Rosenbaum (2004) found that where people took hold of a plunger was partly determined by

[3] Future research could be done to examine this issue further. A possible experiment is one in which gap height or width is varied independently at the start and at the end of the movement. The involvement of precision could also be examined by varying the weight of the object, thereby increasing or decreasing the importance of grasp comfort.
[4] A future experiment that could be done to increase the ecological relevance of the task would be to ask people to pour a bit of sugar out of a bowl through a gap.

the height of the shelf where the plunger had to go, but also in part by the final grasp position on the previous trial. For that task, the grasp position on the object was the same for the start and the end of the movement, but for our bowl grasping task, we could make a distinction between previous trial effects of start and end grasps, showing that it was the final (more recent) grasp position that influenced the next trial, not how participants took hold of the object on the previous trial. Inter-trial effects are in agreement with the posture-based model of grasping (Rosenbaum et al., 1995, 2001), which assumes that movements are planned on the basis of the memory of previous grasps. Recent grasps enter this memory and therefore influence subsequent grasps.

A further factor that may have influenced the grasps in our experiments is the initial spatial location of the bowl. Previous studies have suggested that participants avoid movements that involve leaning over to grasp an object (Rosenbaum, 2008; Rosenbaum et al. 2011; Rosenbaum, 2012). Such tendency to avoid leaning over may have influenced our data, resulting in different grasps for bowl positions that are further away from the participants' initial right hand position. In an additional analysis (data not shown), we examined initial and end comfort of grasps for bowls placed at the four different locations of the Penn State setup[5]. Interestingly, grasps of the bowl in the left-most ring led to a modest end-state comfort effect, while grasps in the right-most ring led to initial state comfort. This suggests that the end-state comfort effect may depend on the initial position of the to-be-grasped object, although it will have to be determined how exactly the initial object position influences grasps.

[5] The analysis of initial bowl position on the end-state comfort effect was only possible for the Penn State setup. In the Aberdeen setup, missing data during automatic tracking led to too few data points per condition for this analysis.

9.1 Task Complexity

Of all the potential explanations that we have considered, the one that seems most promising pertains to task complexity. Participants sometimes ended in very awkward positions and seemed on the next trial to take more time to plan their movement, with mixed outcomes. (We did not measure these times, so we cannot verify this subjective observation at this stage). Corrections of initial grasps were made, possibly in an attempt to improve end-state comfort. We counted these corrections in Experiment 4 and found that they were more frequent if participants grasped without a delay than with a delay. This suggests that participants in their 'default' mode of grasping take less time to plan their movements than would be optimal. However, forcing people to use more time (Experiment 4) did not lead to more end-state comfort. This suggest either that another criterion is used for selecting an initial grasp, or that the task is so computationally demanding that participants choose not to plan copiously but instead try to learn the optimal grasp strategy by simply trying. It would therefore be interesting to examine whether end-state comfort would be observed with extensive training with the task.

From previous findings, we did not expect to see people appearing to be struggling with the task. Combinations of rotation and translation were tested before, for example by Cohen and Rosenbaum (2011), who asked participants to pick up a horizontally oriented plunger to move it to one of several shelves, placing it in an upright position. Participants in this task adopted an end-state comfort strategy. A similar result was obtained by Zhang and Rosenbaum (2008) who asked participants to place their hand on the top of a pan and to rotate and slide it such that a pointer ended in one of several cups. A possible difference between these studies and our task could be that participants were more likely to first rotate and then move the object, which could have made planning easier. In our task, participants either seemed to rotate the bowl while moving it, or wait before rotating it until they reached the target ring.

While all of this seems plausible, there are arguments, however, against an explanation on the basis of complexity. First, we did not find end-state comfort planning when only rotating the bowl (Experiments 2, 4, and 5), which conceptually, appears to be a simpler task, as it only involves rotation (and lifting the bowl). Second, we also found no evidence for an end-state comfort effect when the task was made easier (Experiment 6) and participants were allowed to choose which gap they choose. If planning demands had prevented end-state comfort, it would have been expected that simplifying the task would reintroduce the end-state comfort effect, which is not what we found. Finally, it is unclear what exactly defined the complexity of our task. Intuitively, the bowl grasping task that we employed is more complex than the dowel rotation (e.g., Rosenbaum et al. 1990), plunger transportation (e.g., Cohen and Rosenbaum, 2004) or pan sliding tasks (Zhang and Rosenbaum, 2008). A possible candidate for complexity is the space in which the movement takes place. Rotating a dowel and moving a plunger can be performed in the fronto-parallel plane, while the pan sliding task could be performed in the horizontal plane. Our bowl grasping task involved lifting, moving, and rotating the bowl, which could not be carried out in a single plane. Alternatively, the combination of lifting, moving and rotating the bowl may have created the additional complexity, but without further experiments it unclear what are the critical conditions under which participants no longer apply end-state comfort.

9.2 Measuring End-State Comfort

In this study we used two techniques to determine where people take hold of an object. We used video-recordings, analyzing frame by frame to determine where people grasp the object, and we used automatic analysis of video images using the Mantra software package (Mathot and Theeuwes, 2011). Although an Optotrak system was available, allowing the tracking of markers placed on the objects and the participants' hand, we decided not to use this system because the wires connecting the markers to the computer for recording could have influenced participants' grasps, making grasps involving large joint movements more difficult (pulling the wires). By using video analysis, we could avoid this issue. The manual analysis of the video images did not place any restrictions on the participants. The automatic analysis required participants to wear a glove with a distinct color, but this glove did not cover the fingers and therefore may have only mildly influence people's grasps.

Video analysis has its disadvantages, however. Manual analysis is labor intensive, requiring extraction of the exact frames of taking hold of and releasing the bowl, and marking the location of the thumb on the rim in the extracted images. This process also has a slight subjective component to it. Different people analyzing the images could make slightly different decision on which frames to extract and where to mark the thumb's position, although the effects of these decisions are likely to be small (as illustrated in Figure 1A) and have proven to be small when tested with independent coders (Cohen and Rosenbaum, 2004). The automatic analysis, possibly because of the large joint range movements involved in our task, led to loss of the signal of the hand and/or the bowl on a portion of the trials, and therefore only a subset of trials could be analyzed. Possible ways to avoid such loss of data in future studies would be to use two Mantra setups to track the participants' movements, with cameras placed at different angles so one camera could provide a signal when the other fails. Another method would be to combine the automatic analysis with the manual one (using one Mantra setup with an additional video camera), so the trials in which the automatic analysis fails can be coded by hand. There are now also newer motion tracking systems available that avoid wires. Development of such systems has been promoted by an interest in making video games as realistic as possible, and therefore movements of actors are used, which are recorded using systems such as the Vicon system, the Qualisys system or the Metamotion system. Developments in this field may therefore also solve some of the issues addressed here, although it must be noted that the commercially available systems tend to be costly and may therefore not be available to everyone.

We also used two measures to estimate the comfort of the grasps of the participants. First, we used a 'comfort zone' method, based on grasps made by participants, assuming that participants most frequently grasp an object (or end their movement) with a comfortable grasp. We either used all trials (Experiments 1, 3 and 6, where our design did not include 'lift' trials, where participants grasped the bowl just to lift it), or a portion of the trials (Experiments 2, 4, and 5, using 'lift' trials only), resulting in very similar results across experiments. We used one single comfort zone across participants, based on the data of all participants. Future studies could use individual comfort zones instead, by including more 'lift' trials, ensuring sufficient data to correctly estimate the position and location of the zones for each individual participant. Future experiments could also use a separate block of trials to estimate the preferred grasping position, by asking participants repeatedly to grasp the object and lift it. In the present experiment, we mixed the lift-only trials with the other trials, and therefore previous grasps may have influenced where people took hold of the bowl when grasping it to simply lift it, influencing the position of the comfort zone.

It is, however, reassuring that overall our 'comfort zone' findings were in line with our comfort rating approach, even though sometimes a grasp inside the comfort zone was not rated as highly comfortable, and even though some areas outside the comfort zone were rated as somewhat comfortable. We used two types of comfort ratings. In one rating task, we asked participants to decide from a set of randomly selected trials whether the start grasp or end grasp (grasps not labeled) looked more comfortable. In a second rating task, we took pictures of one of the experimenters taking hold of the bowl at different sites and asked participants to rate the perceived comfort of the grasp on a 1-7 scale. From these ratings, we computed the estimated comfort for each thumb position on the rim for each of the rings in which the bowl could be placed. The first of these strategies appears to lead to ratings that are in better agreement with the comfort zone than the second of the strategies (Figure 2E versus 3C). Why this may be the case, is unclear at this point, and should be investigated in future studies. Another rating task that may be adopted at this point would be the rating task introduced by Rosenbaum et al. (1990), who asked participants, rather than looking at an image, to take hold of the object and to rate the perceived comfort. This task has the advantage that it may add proprioceptive information on which the rater can base his or her decision. However, it is also more time-consuming and may therefore need to rely on fewer participants than the visual rating tasks, where it is more straightforward to collect data from a large set of participants.

9.3 Conclusion

In six experiments we investigated whether the end-state comfort effect extends to a more complex object manipulation task than has been used before, involving a continuous grasp selection and a combination of the translation and rotation of an object. In contrast to previous studies, no support was found for end-state comfort planning. The absence of an end-state comfort effect was not due to a lack of planning time or strong restrictions on the grasping movements. Our results indicate that there are tasks for which participants do not achieve end-state comfort. Future studies should reveal how many such tasks there are and what their defining properties are.

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FIGURE CAPTIONS

Figure 1. Setup and data analysis. [A] Picture of the setup used in Experiments 1, 3 and 6, showing how grasps were analyzed offline. The thumb position on the rim was determined using a Matlab script that allowed the user to click on the thumb position in the image from the video. The rim position and diameter was determined in a similar way, allowing for the measurement of thumb position in degrees along the rim. [B] Image of the experimenter placing the block to denote the target gap in Experiment 3. [C] Illustration of the rating task of Experiment 1. Participants were asked to indicate whether they thought the left or the right grasp looked more comfortable. [D] Image generated via Mantra software (Mathot and Theeuwes, 2011), recording the position of the bowl and the position of the hand in Experiments 2, 4, and 5. [E] Analysis of the Mantra recordings. Green circles denote bowl samples where the bowl was moving (automatic detection by Mantra), the red circles where the bowl was still. The blue connected samples show the hand position. The black solid lines show the estimated start and end grasp.

Figure 2. Results of Experiment 1. [A] The frequencies of different grasp positions in the experiment, expressed as an angle around the rim of the bowl, differentiating between start (red solid line) and end (dotted blue line) grasps. [B] Graphical illustration of the 'Comfort zones', computed on the basis of the median grasp position (dotted vertical lines in [A]), plus and minus 45 degrees. [C] Frequency of grasps inside the comfort zone, distinguishing between trials with both comfortable initial and final grasps ('both'), trials where the initial and final grasp were both outside the comfort zone ('neither'), trials with a comfortable initial grasp ('start') and trials with a comfortable final grasp ('end'). [D] Estimated comfort for start and end grasps, based on a weighted grasp frequency measure also suggests an

initial-state comfort effect. [E] Frequency of trials in which a group of rates judged the initial grasp ('start') or final ('end') grasp to be more comfortable for a set of randomly selected trials. A third category was used, allowing raters to decide both grasps were equally comfortable ('Equal'). [F] Graphical illustration of the proportion of trials in which a grasp with each grasp position was rated more comfortable than the other grasp (either start or final) on that trial, providing an estimate of comfort for each grasp position. [G] Estimates of the comfort of initial and final grasps (on the basis of the numbers in [F]. [H] Plots of inter-trial effects, examining whether participants use the same grasp that they ended with before (top plot) or use the same grasp that they started with before (bottom plot). Different colors represent data of different participants. In the bar graphs, the error bars denote the standard error of the mean across participants.

Figure 3. Results of Experiment 2. [A]. Comfort zones estimated on the basis of the average grasp position in the 'lift' trials, with the width of the intervals determined by the standard deviation across participants. [B]. Percentage of trials with a grasp inside the comfort zone for translation and rotation trials and rotation only trials. [C] Estimated start and end comfort based on weighted lift grasp frequencies. [D]. Estimated comfort based on comfort ratings in [E]. [D]. Polar plots showing the average comfort ratings (1=very uncomfortable, 5=very comfortable) for each of the bowl positions.

Figure 4. Results of Experiment 3 in which the instruction where to move the bowl was provided with a visual cue (a wooden block placed near the target gap). [A]. The percentage of grasps inside the comfort zone (the median grasp position plus and minus 45 degrees), revealing no difference between the comfort of start and end postures. [B] Comfort estimates based on weighted grasp frequencies. [C]. Estimated comfort of start and end

grasps (based on the ratings from Experiment 1), again revealing no difference between start and end postures.

Figure 5. Results of Experiment 4. [A] and [B]. Percentage of trials with grasps in the 'comfort zone' (based on the grasps in the lift-only trials), for combined translation and rotation trials and rotation-only trials for the 'no-delay' and 'delay' conditions, respectively. [C] and [D] Estimated comfort based on weighted lift-grasp frequencies for 'no-delay' and 'delay' trials. [E] and [F]. Estimated comfort (on the basis of the ratings of Experiment 2) for combined translation and rotation trials and rotation-only trials for the 'no-delay' and 'delay' conditions, respectively.

Figure 6. Examining the effects of practice. [A]. The percentage of grasps inside the comfort zone in the 1st (green bars) and 2nd session (blue bars) for the different types of movements. [B] Estimated comfort across the two sessions based on weighted lift-grasp frequencies. [C]. The estimated comfort across the two sessions (left and right group of bars), comparing start and end comfort (red and green bars) for combined translation and rotation movements (left) and rotation only (movements).

Figure 7. Results of Experiment 5. [A]. The percentage of trials in which participants choose a grasp with their thumb inside the bowl's rim. [B]. The percentage of 'thumb-inside' grasps per movement type (translation+rotation, rotation-only, lift). [C]. Percentages of grasps in the 'comfort zone' (based on the grasps in the lift trials). [D] Estimated comfort based on lift-grasp frequencies.

Figure 8. Results of Experiment 6. [A]. The percentage of trials in which participants chose gap A, B, C when starting from gaps A, B, and C, suggesting that participants preferred movements involving little rotation. [B]. The frequency of grasps inside the comfort zone (based on the distribution of all grasps). [C] Estimated comfort based on weighted grasp frequencies. [D]. The estimated comfort of start and end grasps, based on the ratings of Experiment 1.

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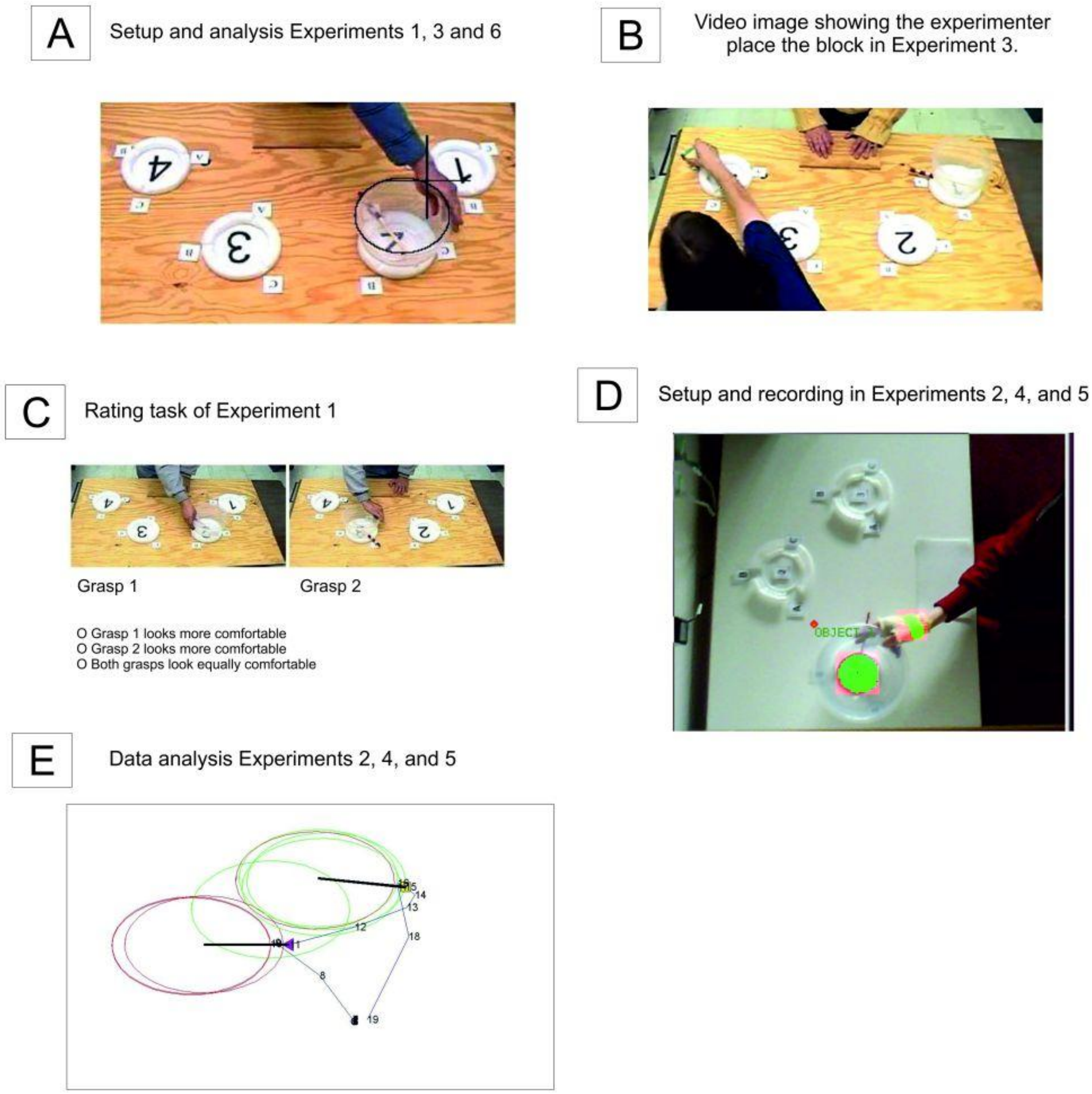

Figure 1.

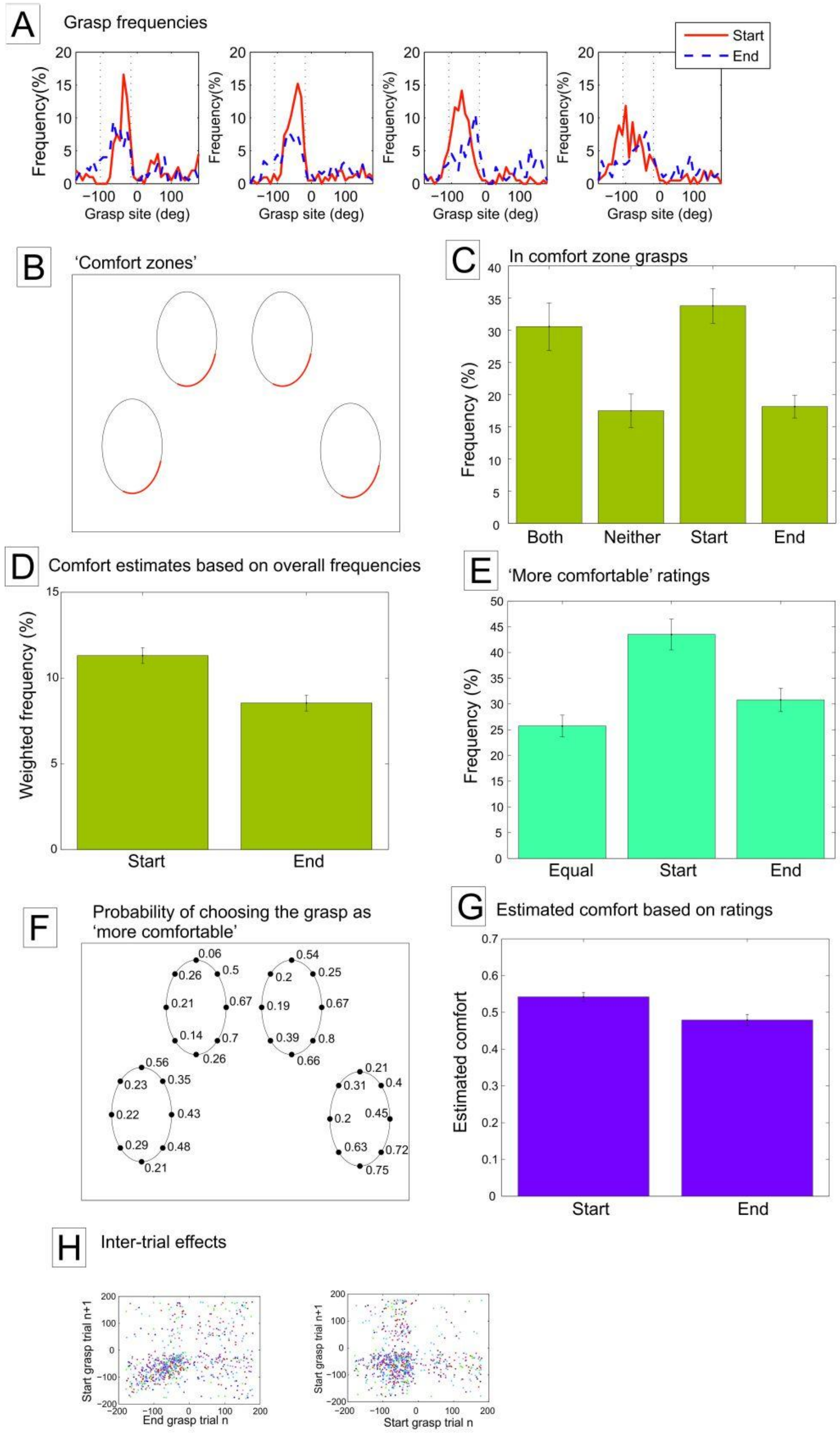
A
Grasp frequencies
Start
End
Frequency(%)
Grasp site (deg)
B
'Comfort zones'
C
In comfort zone grasps
Frequency (%)
Both
Neither
Start
End
D
Comfort estimates based on overall frequencies
Weighted frequency (%)
Start
End
E
'More comfortable' ratings
Frequency (%)
Equal
Start
End
F
Probability of choosing the grasp as 'more comfortable'
G
Estimated comfort based on ratings
Estimated comfort
Start
End
H
Inter-trial effects
Start grasp trial n+1
End grasp trial n
Start grasp trial n

Figure 2.

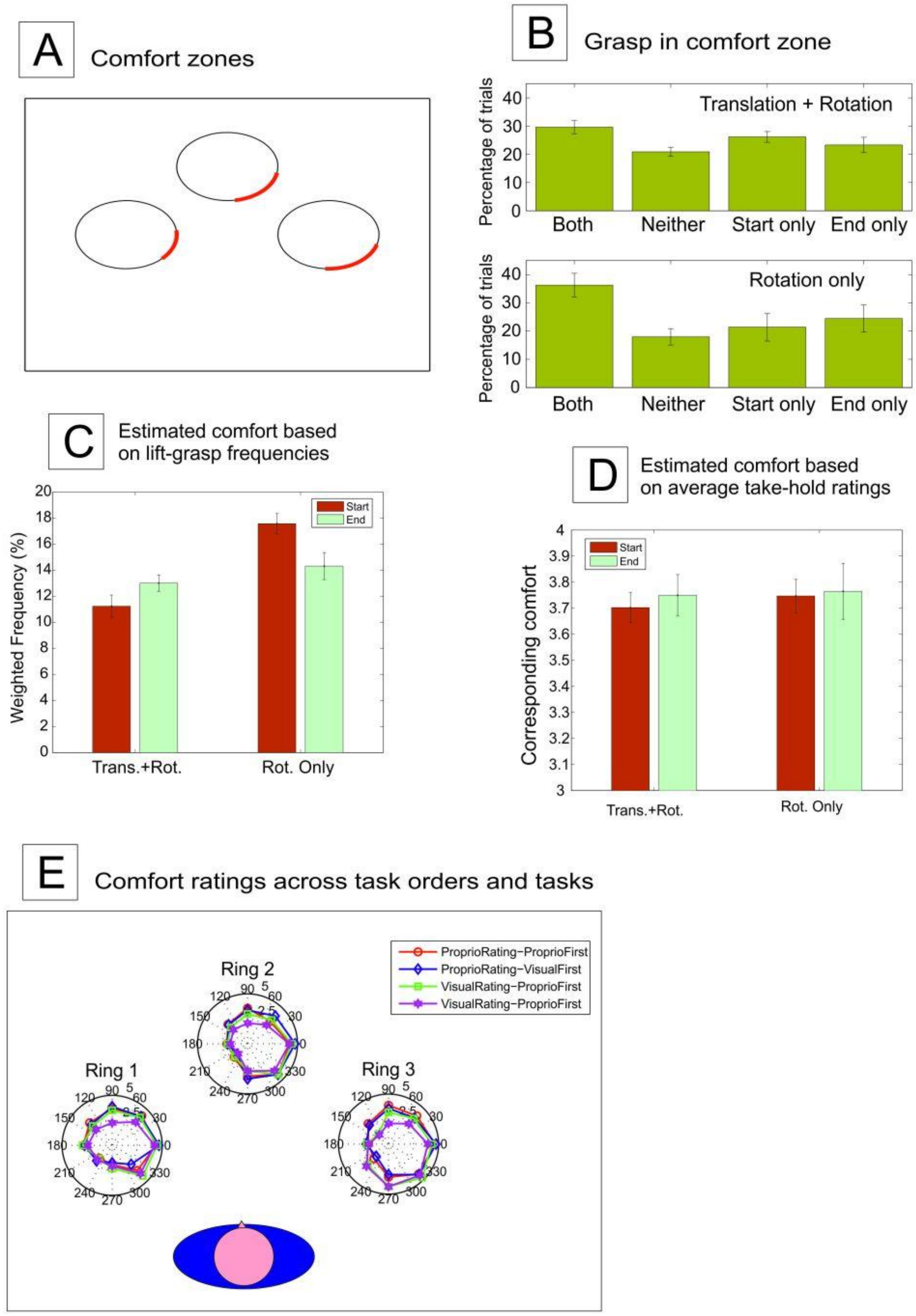
A
Comfort zones
B
Grasp in comfort zone
Translation + Rotation
Percentage of trials
Both
Neither
Start only
End only
Rotation only
C
Estimated comfort based on lift-grasp frequencies
Weighted Frequency (%)
Start
End
Trans.+Rot.
Rot. Only
D
Estimated comfort based on average take-hold ratings
Corresponding comfort
E
Comfort ratings across task orders and tasks
Ring 1
Ring 2
Ring 3
ProprioRating−ProprioFirst
ProprioRating−VisualFirst
VisualRating−ProprioFirst
VisualRating−ProprioFirst

Figure 3.

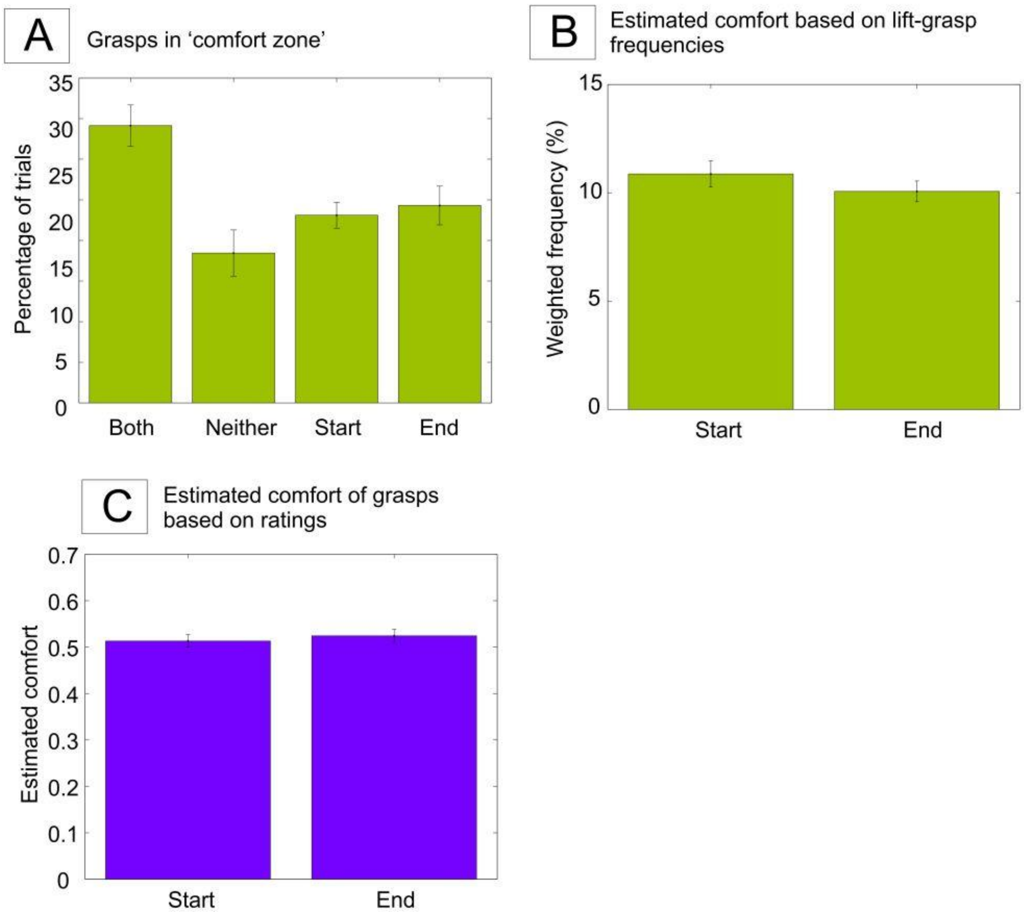
A
Grasps in 'comfort zone'
Percentage of trials
35
30
25
20
15
10
5
0
Both
Neither
Start
End
B
Estimated comfort based on lift-grasp frequencies
Weighted frequency (%)
15
10
5
0
Start
End
C
Estimated comfort of grasps based on ratings
Estimated comfort
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Start
End

Figure 4.

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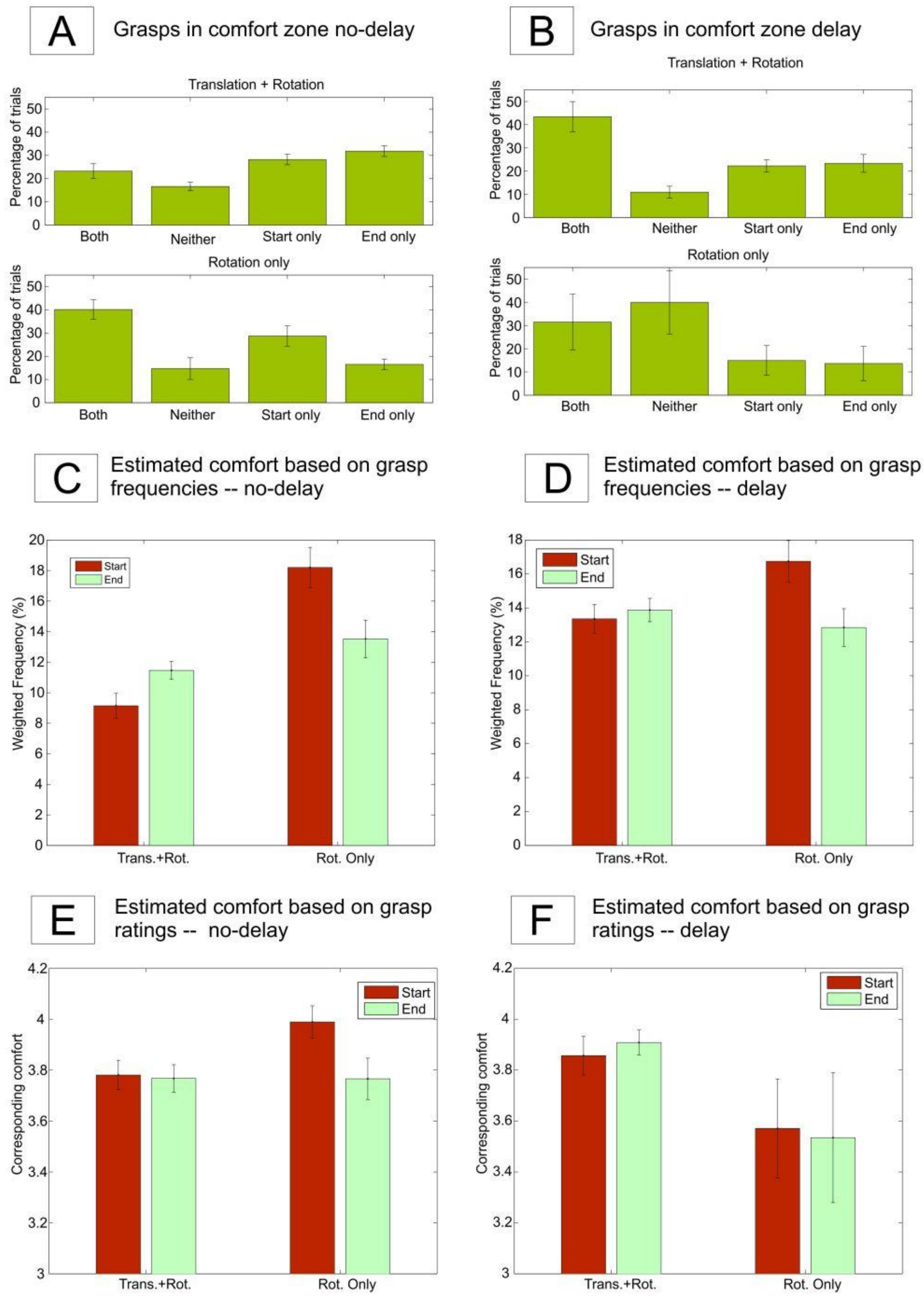

Figure 5.

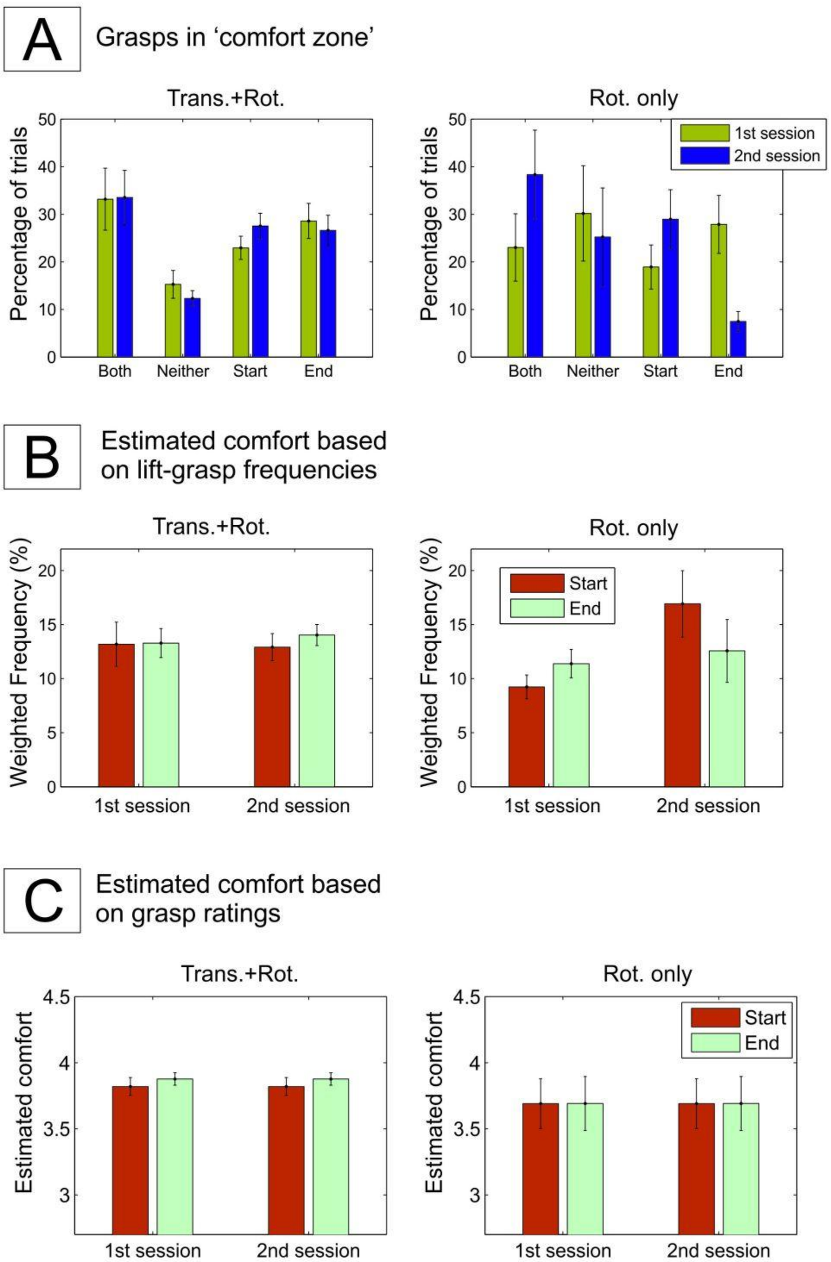
A
Grasps in 'comfort zone'
Trans.+Rot.
Rot. only
Percentage of trials
0
10
20
30
40
50
Both
Neither
Start
End
1st session
2nd session
B
Estimated comfort based
on lift-grasp frequencies
Weighted Frequency (%)
0
5
10
15
20
1st session
2nd session
Start
End
C
Estimated comfort based
on grasp ratings
Estimated comfort
3
3.5
4
4.5

Figure 6.

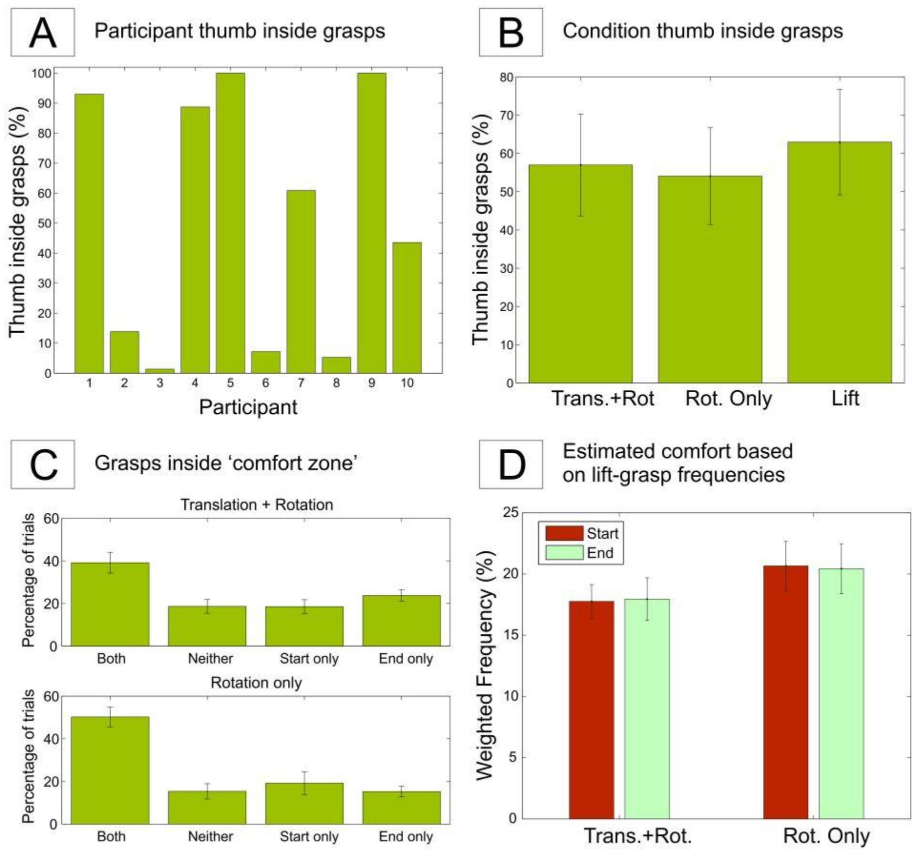
A
Participant thumb inside grasps
Thumb inside grasps (%)
Participant
B
Condition thumb inside grasps
Thumb inside grasps (%)
Trans.+Rot
Rot. Only
Lift
C
Grasps inside 'comfort zone'
Translation + Rotation
Percentage of trials
Both
Neither
Start only
End only
Rotation only
D
Estimated comfort based
on lift-grasp frequencies
Start
End
Weighted Frequency (%)
Trans.+Rot.
Rot. Only

Figure 7.

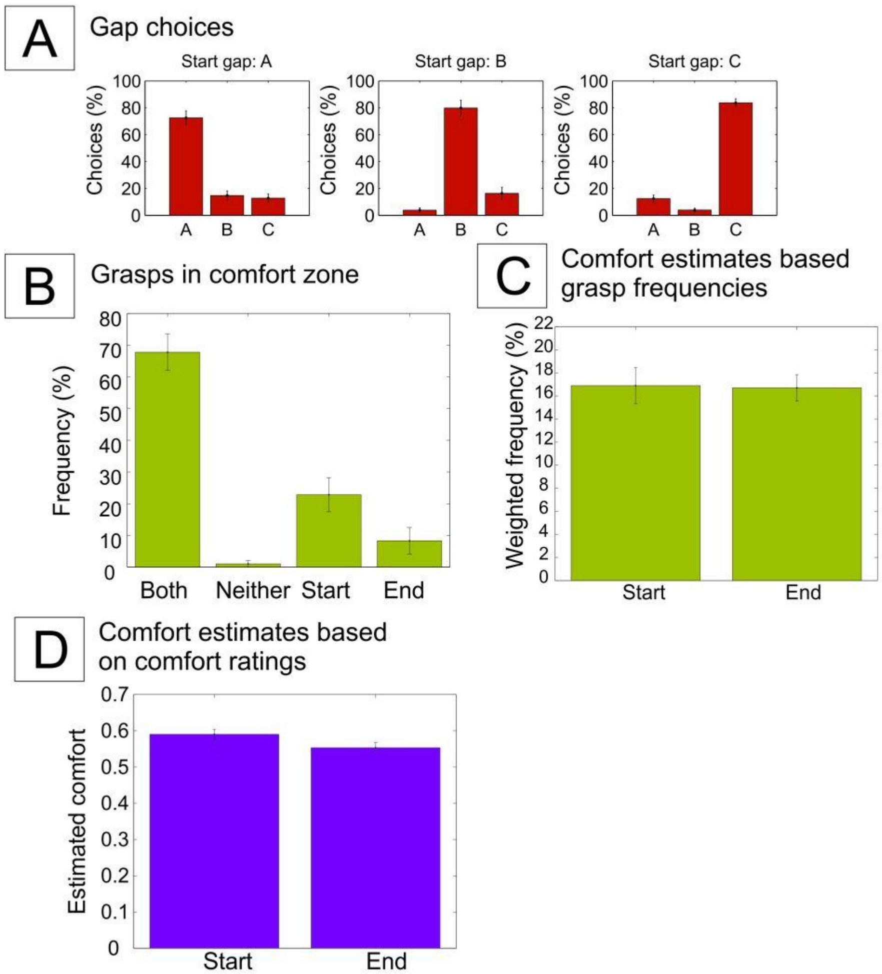
A
Gap choices
Start gap: A
Start gap: B
Start gap: C
Choices (%)
100
80
60
40
20
0
A B C
B
Grasps in comfort zone
Frequency (%)
80
70
60
50
40
30
20
10
0
Both
Neither
Start
End
C
Comfort estimates based
grasp frequencies
Weighted frequency (%)
22
20
18
16
14
12
10
8
6
4
2
0
Start
End
D
Comfort estimates based
on comfort ratings
Estimated comfort
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Start
End

Figure 8.