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The End-State Comfort Effect in Bimanual Grip Selection

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During a unimanual grip selection task in which people pick up a lightweight dowel and place one end against targets at variable heights, the choice of hand grip (overhand vs. underhand) typically depends on the perception of how comfortable the arm will be at the end of the movement: an end-state comfort effect. The two experiments reported here extend this work to bimanual tasks. In each experiment, 26 right-handed participants used their left and right hands to simultaneously pick up two wooden dowels and place either the right or left end against a series of 14 targets ranging from 14 to 210 cm above the floor. These tasks were performed in systematic ascending and descending orders in Experiment 1 and in random order in Experiment 2. Results were generally consistent with predictions of end-state comfort in that, for the extreme highest and lowest targets, participants tended to select opposite grips with each hand. Taken together, our findings are consistent with the concept of constraint hierarchies within a posture-based motion-planning model.

Key words: movement planning, object transport

When people reach for an object, pick it up, and transport it to another location, many movement options are available to complete the task. An interesting problem, therefore, is how an individual selects a particular movement from the many available options, or what Bernstein (1967) referred to as the degrees of freedom problem. Recent theorizing by Rosenbaum and his colleagues (Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995; Rosenbaum, Meulenbroek, & Vaughan, 2001; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001) suggested that humans rely on a posture-based motion planning system in which stored postures are evaluated as to how well they satisfy the demands of the task, followed by selection of a goal posture that best meets the task constraints. Finally, a movement to that goal posture is specified (Rosenbaum, Meulenbroek, & Vaughan, 2001).

The research reported in this article is related to a specific aspect of a posture-based movement perspective—the end-state comfort effect (Rosenbaum & Jorgensen, 1992; Rosenbaum et al, 1990; Rosenbaum, van Heugten, & Caldwell, 1996). The effect illustrates the tendency to minimize awkward hand and arm postures at the end of simple object manipulation tasks rather than at the beginning. Humans appear to be willing to adopt awkward initial postures to ensure comfortable ending postures. Consider, for example, the task of picking up an overturned glass from a table and turning the glass right side up (this task was anecdotally described by Rosenbaum et al., 1990). The task is most commonly performed by initially grasping the glass with an awkward, pronated grip (thumb-down grip), and then completing the task by supinating the hand, thus ending with a comfortable, thumb-up posture. Performing the task in the reverse sequence, although certainly possible, would place the hand in an uncomfortable ending posture and might make it more difficult to execute a subsequent movement.

Studies of the end-state comfort effect have used a variety of tasks, such as rotating a handle (Rosenbaum

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et al., 1996, Experiment 1; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1992), reaching (Fischer, Rosenbaum, & Vaughan, 1997), and pronating-supinating a stick (Rosenbaum et al., 1996, Experiment 2). However, a more popular task has been the unimanual "bar-transport" task, in which the participant uses either an overhand or underhand grip to pick up a bar, such as a dowel, and stand one side on end (Fischman, 1998; Rosenbaum et al., 1990; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992) or touch one end to targets at different heights (Rosenbaum & Jorgensen, 1992; Short & Cauraugh, 1997, 1999). The latter variation of the bar-transport task is the focus of the present experiments.

Rosenbaum and Jorgensen (1992) asked 10 participants to pick up a lightweight dowel with their right hand and place the left and right ends against 14 targets at variable heights ranging from 13 to 208 cm above the floor. The dowel rested in a cradle positioned on a table to the left of the targets so that the participants had to reach across their body to pick up the dowel. Participants performed four conditions in which they were instructed to place the left and right ends to each target in systematic ascending and descending orders. After placing the end of the dowel against the instructed target number, participants returned the dowel to the cradle.

With the dependent measure being the type of grip selected (overhand vs. underhand), Rosenbaum and Jorgensen (1992) found that when the task was to place the left end of the dowel against the higher targets (#1–7), or to place the right end against the lower targets (#8–14), most participants picked up the dowel with an underhand grip. However, when the task was to place the left end of the dowel against the lower targets, or the right end against the higher targets, participants preferred the overhand grip. Rosenbaum and Jorgensen also found that because of the systematic ascending and descending orders of target presentations, participants persisted with the grip used on a previous trial until it became too awkward, possibly because of the costs associated with anticipating a transition from one grip to another.

Rosenbaum and Jorgensen's (1992) results were essentially replicated in a series of experiments by Short and Cauraugh (1997), who used a lightweight dowel (Experiment 1) and a heavier dumbbell (Experiment 3). They also tested a considerably greater number of participants compared to Rosenbaum and Jorgensen (1992), with 48 and 30 in their first and third experiments, respectively. In Short and Cauraugh's experiments, target heights were adjusted to each participant's shoulder height, and the order of target locations was randomized. Short and Cauraugh (1999, Experiment 2) measured participants' accuracy (mean radial error) in placing the dowel to the different height targets and found that accuracy was maximized when the arm was in a comfortable ending position, thus supporting a precision explanation of the end-state comfort effect.

Support for the end-state comfort effect in previous work using bar-transport tasks has been limited to using only one hand. The purpose of the present experiments was to test the generalizability of the effect in bimanual tasks. In the two experiments reported here, participants were presented with two dowels, positioned side-by-side and instructed to pick up both dowels simultaneously, placing either the right or left ends to different height target locations. In Experiment 1, the targets were tested in systematic ascending and descending orders, similar to Rosenbaum and Jorgensen (1992), while in Experiment 2, the targets were presented in random order, as in Short and Cauraugh (1997, 1999). The systematic ascending and descending orders affords the opportunity to anticipate the upcoming location (after the first few trials), whereas the random order does not. Consequently, the planning processes may be different for the two types of sequences. In addition, the bimanual task is interesting in that the end-state comfort effect would presumably predict an opposite pattern of grip selections with each hand, with the effect being especially strong at the extreme high and low targets. For example, if participants are sensitive to maximizing end-state comfort, then placing the left end of the dowels to the higher targets should result in choosing an overhand grip with the left hand and an underhand grip with the right hand. For the lower targets, we should find the opposite pattern of grip selection, that is, an underhand grip with the left hand and an overhand grip with the right hand. Of course, when the task is to place the right end of the dowels to the targets, these patterns would simply be reversed. As the targets are systematically ascended or descended, there should be a point where the two hands switch their grips—a point-of-change effect (Short & Cauraugh, 1997). Experiment 1 was designed to test these predictions.

Experiment 1

Method

Participants

Twenty-six right-handed undergraduate students from Auburn University, with a mean age of 20.4 years, participated in exchange for course credit. After giving informed consent, participants read a set of instructions describing the nature of the task they were to perform. Participants were naive with respect to the task and experimental hypothesis being tested.

Apparatus

The apparatus consisted of the side of a large wooden cabinet on which 14 horizontal strips of masking tape were spaced 15 cm apart. The highest strip was 210 cm above the floor, and the lowest strip was 14 cm from the floor. The center of each strip contained a small circular paper disk with a number from 1 (top location) to 14 (bottom location) inscribed inside the disk. Two small black circles, which served as targets for placing the dowels, were drawn 5 cm to the left and right of each of the numbered disks. To the left of the cabinet was a standard-height table (74.3 cm) containing two pair of bookends (22.9 cm high), on which two lightweight wooden dowels (30.5 cm long, 1.9 cm diameter) rested. The dowels were painted black on one end and white on the other, with the black end always facing left. The bookends and one edge of the table were oriented at a 135° angle with respect to the cabinet.

Procedure and Design

Participants stood facing the cabinet behind a line taped to the floor at a distance of 30.5 cm. Their body midline was positioned directly opposite the numbered disks, and their hands were at their sides. A trial began with the experimenter giving an instruction, such as "black to 1" or "white to 14." The participants then reached over, picked up the left dowel with their left hand and the right dowel with their right hand, and placed the instructed ends to the corresponding target. The dowels were then returned to the bookends in their original position (i.e., black ends facing left). Participants returned their hands to their sides and waited for the next instruction. Each target location was tested only once per condition. Following each trial, the experimenter recorded the grip choice (overhand or underhand) for each dowel. When picking up the dowels, participants were told they could use overhand grips, underhand grips, or a combination of both. They were also instructed to firmly grasp the dowels in the center, not to change their grip after picking up the dowels, and to place the dowels against the target circles so that they pointed straight into the cabinet. To avoid the possibility of lower back strain, participants were instructed to bend their knees for the lower targets.

Each participant performed in four conditions identical to those used by Rosenbaum and Jorgensen (1992). The conditions involved (a) bringing the left ends of the dowels to the targets in a systematic ascending order; (b) bringing the left ends of the dowels to the targets in a systematic descending order; (c) bringing the right ends of the dowels to the targets in a systematic ascending order; and (d) bringing the right ends of the dowels to the targets in a systematic descending order. The four conditions were tested in a balanced order using all possible combinations, with participants being randomly assigned to a particular order. The experiment required approximately 20 min per participant.

Results and Discussion

Participants made no errors in placing the ends of the dowels to the correct target positions; therefore, all trials were used in the probability calculations. The data are shown in Figures 1 and 2, corresponding to cases in which the left (black) and right (white) ends of the dowels, respectively, were brought to the targets. The graphs display the probability of picking up the dowels with an overhand grip as a function of hand and target position. The X-axis of each graph is organized to read from left to right, corresponding to the order in which the targets were touched. Thus, for the descending order, high targets are on the left end of the axis, and low targets are on the right; but for the ascending order, low targets are on the left end of the axis, and high targets are on the right.

Left End to Targets

When the task was to bring the left end of the dowels to the targets, qualitative analyses of the data and figures revealed results fairly consistent with predictions

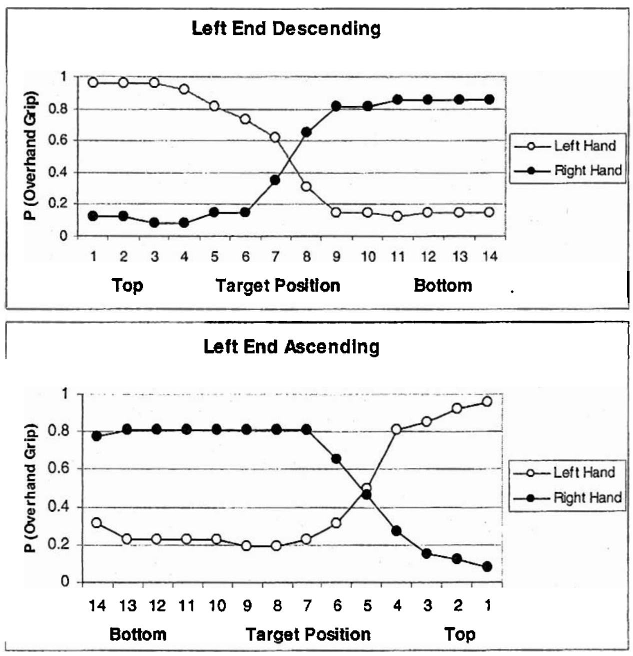

Figure 1. Probability of picking up the dowels with an overhand grip when the task was to bring the left (black) end of the dowels to the targets, Experiment 1.

based on end-state comfort. That is, with the left hand, participants tended to select overhand grips for the higher targets and underhand grips for the lower targets. With the right hand, by contrast, participants tended to select underhand grips for the higher targets and overhand grips for the lower targets. Thus, as seen in Figure 1, the extreme target positions produced opposite grip selections for each hand. Such a strategy allowed both hands to achieve identical postures at the end of the movement, with the fingers wrapped around the top of the dowel and the thumb underneath for the high targets, and the fingers wrapped around the bottom of the dowel and the thumb on top for the low targets. In addition, as the figure shows, the psychophysical function was affected by whether the targets were tested in an ascending or descending order. That is, for the ascending condition, a point of uncertainty occurred fairly late in the sequence, at Targets #6 and 5, where the probability of selecting either grip with either hand was not significantly different. This observation was confirmed by chi square analyses, which revealed nonsignificant differences between the left and right hands at Target #6, χ^2 (2, N= 26) = 3.15, $p > .05$, and at Target #5, χ^2 (2, N= 26) = 0.08, $p > .05$. For all other targets, opposite grips were selected by the left and right hands, all χ^2 values > 5.99, $ps < .05$.

For the descending condition, however, a point of change occurred around the middle of the sequence, between Targets #7 and 8. At Target #7, χ^2 (2, N= 26) = 1.92, and at Target #8, χ^2 (2, N= 26) = 3.15, both $ps > .05$. This result is similar to that of Short and Cauraugh (1997, Experiment 1), although their targets were presented in a random order and the starting target was adjusted according to participants' height.

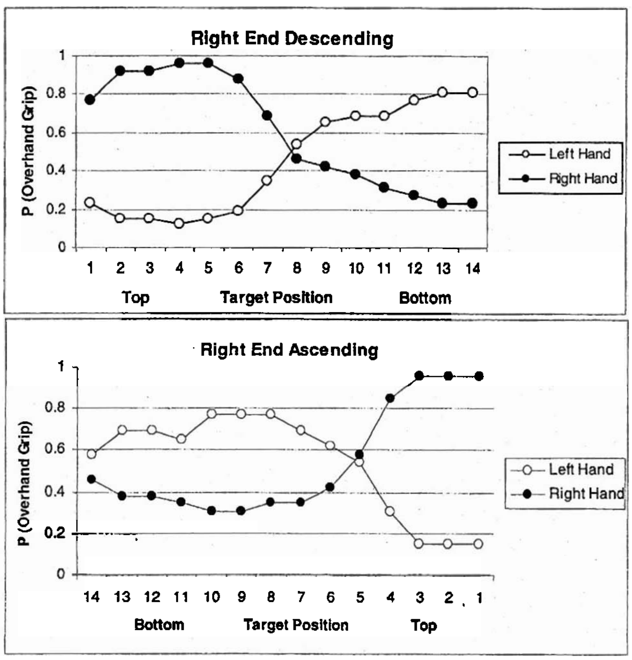

Figure 2. Probability of picking up the dowels with an overhand grip when the task was to bring the right (white) end of the dowels to the targets, Experiment 1.

Right End to Targets

When the task was to bring the right end of the dowels to the targets, we found differences depending on whether the targets were tested in an ascending or descending order, with the descending order producing a pattern more consistent with end-state comfort predictions (see Figure 2). For the descending order, the higher targets (#1–6) produced opposite grips with each hand, with all χ^2 values > 5.99, $ps < .05$. The three lowest targets (#12, 13, and 14) also produced opposite grips with each hand, with all χ^2 values again > 5.99, $ps < .05$. For Targets #7 through 11, the probability of selecting either grip with either hand was not significantly different, with all χ^2 values < 5.99, all $ps > .05$.

The right end ascending sequence produced a different pattern of grip selections than the other sequences. For this condition, the left and right hands selected opposite grips only for the four highest targets (#4, 3, 2, and 1), with all χ^2 values > 5.99, $ps < .05$. Thus, the opposite-grip effect was stronger for the higher targets than for the lower targets, where sensitivity to end-state comfort did not seem to be an important constraint in choosing grips. Why? We tentatively suggest that because participants were able to bend at the knees to reach the lower targets, they could pick up the dowels with any grip configuration and then use a combination of pronation and supination at the radio-ulnar joint and radial and ulnar deviation at the wrist, to achieve a comfortable ending posture. However, we did not observe this behavior for any other sequence. Therefore, for now, we will treat this finding as an anomaly, but one that certainly deserves further study.

Experiment 2

With the exception of the right end ascending condition, the results of Experiment 1 were generally consistent with our hypotheses based on end-state comfort and with previous work using unimanual tasks (Rosenbaum & Jorgensen, 1992). The purpose of Experiment 2 was to test the bimanual end-state comfort effect, but with random presentation of target locations (Short & Cauraugh, 1997, 1999). As stated in the introduction of this article, the random order of target presentations makes it difficult to anticipate the upcoming location and may require different planning processes.

Method

Participants

Twenty-six Auburn University undergraduate students, all right-handed, with a mean age of 21.3 years, participated in exchange for course credit. No student had participated in Experiment 1, and all were naive with respect to the task and hypothesis being tested. Once participants gave informed consent, they read a set of instructions describing the nature of the task they were to perform.

Apparatus

The apparatus was identical to that used in Experiment 1.

Procedure and Design

The procedures were essentially the same as those used in Experiment 1 but with the following exceptions. Only two conditions were tested, which were identical to those used by Short and Cauraugh (1997, Experiment 1). The conditions involved bringing the left and right ends of the dowels to the targets in random order. Each participant was assigned to a different random order of the 14 targets, and the order for each participant also differed for the left and right ends. Half the participants performed the left end condition first and the right end second; the other half received the opposite order. All other procedures were the same as in Experiment 1.

Results and Discussion

Participants made no errors in placing the ends of the dowels to the correct target positions; therefore, all trials were used in the probability calculations. The data are shown in Figure 3, with the right end presented in the top panel and the left end in the bottom panel. High targets appear at the left end of the X-axis; low targets are to the right.

Left End to Targets

When the task was to bring the left end of the dowels to targets presented in random order, participants produced a pattern of results fairly consistent with the end-state comfort effect in that the extreme high and low targets tended to produce opposite grips with each hand. This result, however, was somewhat more pronounced at the lower end of the target display than at the higher end. Chi-square analyses revealed a significant opposite-grip effect for the three highest targets (#1, 2, and 3), with all χ^2 (2, N = 26) values > 5.99, ps < .05. At the lower end of the target display, six targets (#9 through 14) exhibited opposite-grip choices for the two hands, with all χ^2 (2, N = 26) values > 5.99, ps < .05. The opposite-grip effect at target locations between #4 and 8 was nonsignificant, all χ^2 values < 5.99, ps > .05.

Right End to Targets

The pattern of results for this condition was similar to the previous condition, with the following exceptions. At the lower end of the target display, only the four lowest targets (#11 through 14) exhibited a significant opposite-grip effect, with all χ^2 values > 5.99, ps < .05. The opposite-grip effect at target locations between #4 and 10 was nonsignificant, all χ^2 values < 5.99, ps > .05. Thus, there was a slightly larger range of indifference when the right end of the dowels touched the targets, compared to the left end.

General Discussion

Does the end-state comfort effect, found in unimanual bar-transport tasks (Rosenbaum & Jorgensen, 1992; Short & Cauraugh, 1997, 1999), appear in more complex bimanual tasks? This was the major question

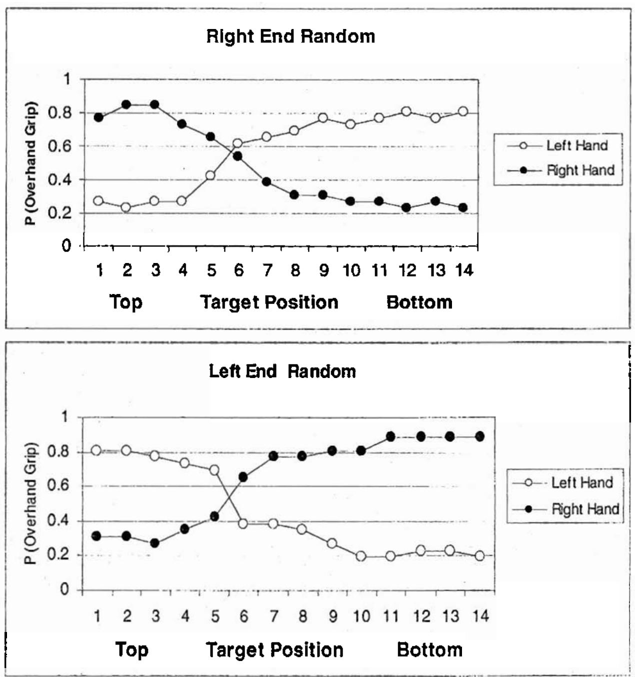

Figure 3. Probability of picking up the dowels with an overhand grip. The top panel shows the data for the right (white) end, and the bottom panel shows the data for the left (black) end, Experiment 2.

addressed in the two experiments reported here. Our answer, based on the grip selection preferences of our participants, is a tentative yes. For the extreme highest and lowest targets, participants tended to select opposite grips with each hand, which is consistent with a strategy designed to maximize comfort at the end of the movement. However, the effect was not as dramatic as in the unimanual studies. In both experiments, we found no condition in which every participant performed the task the same way. The highest agreement we achieved was 96% (25 of the 26 participants) for several target locations in each experiment. By contrast, Rosenbaum and Jorgensen (1992) and Short and Cauraugh (1997) found several target locations that produced 100% agreement among their participants. There were also other differences between the present results and those of the unimanual research, and it might prove useful in the beginning of this discussion to compare our data to that of Rosenbaum and Jorgensen (1992) and Short and Cauraugh (1997). We then address the issue of how the present experiments fit within the context of a posture-based motion-planning model (Rosenbaum, Meulenbroek, & Vaughan, 2001; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001).

We can make somewhat of a direct comparison between our results and those of Rosenbaum and Jorgensen (1992) and Short and Cauraugh (1997), if we examine only the right-hand performance of our participants. However, we acknowledge that the task executed by the right hand in the bimanual condition may not necessarily be the same task as performed by that hand in the unimanual environment in terms of perceptual processes, planning processes, and motor processes. To illustrate this point, there are examples of differences in coordination patterns that can result between unimanual and bimanual drawing tasks (e.g., Franz, 1997; Franz, Zelaznik, & McCabe, 1991).

Comparison to Rosenbaum and Jorgensen (1992)

For the left end descending order, Rosenbaum and Jorgensen (1992) found that approximately 80% of their participants used an overhand grip for eight targets beginning at the midpoint of the sequence (Target #7) and continuing to the lowest target (#14). In our study, only the last six targets (#9–14) produced similar results, with over 80% of the participants using the overhand grip (see Figure 1). At the higher targets (#1–6), our pattern of results differs markedly from Rosenbaum and Jorgensen's. Relatively few of our participants (8–15%) used an overhand grip for the six highest targets, whereas Rosenbaum and Jorgensen found a fairly systematic increase in the number of overhand grips, beginning at about 20% for Target #1 and reaching 50% for Targets #5 and 6 (see their Figure 2, p. 66).

For the left end ascending order, there were also differences between our findings and those of Rosenbaum and Jorgensen (1992). In their study, all 10 participants used an overhand grip for the first eight targets (#14–7), which is in agreement with predictions based on end-state comfort. In our study, by contrast, only 77–81% of the participants used an overhand grip for those targets, with about 5–6 participants content to use an underhand grip. At the highest targets (#3, 2, and 1), where using an underhand grip maximizes end-state comfort, Rosenbaum and Jorgensen (1992) found over 30% of their participants used the overhand grip, whereas very few of our participants did so (8–15%).

When the right end of the dowel was brought to the targets, our right-hand results also exhibited differences compared to Rosenbaum and Jorgensen (1992). For the right-end descending order, their participants showed a clear preference for the underhand grip at the six lowest targets (#9–14), with about 90% selecting that grip (estimated from their Figure 2). Among our participants, the preference for the underhand grip at the lowest targets was not as extreme, ranging from 58% at Target #9 to 77% at Targets #13 and 14. At the highest targets (#1–4), approximately 80% of Rosenbaum and Jorgensen's participants used the overhand grip. The values in our experiment were somewhat higher, ranging from 77% at Target #1 to 96% at Targets #4 and 5.

For the right-end ascending order, once again there were substantial differences between our findings and those of Rosenbaum and Jorgensen (1992). Their participants showed a clear preference (about 90%) for the underhand grip at the six lowest targets (#14–9), thus replicating their results for the descending sequence. Our study revealed a much lower preference for the underhand grip, beginning at 54% for Target #14, then increasing to 69% at Targets #10 and 9, and decreasing to 58% at Target #6. At the highest targets (#3, 2, and 1), where the overhand grip would be expected, based on end-state comfort, nearly all of our participants (96%) used that grip, compared to only 75–80% of Rosenbaum and Jorgensen's.

Comparison to Short and Cauraugh (1997)

Our Experiment 2 results for the right hand can be compared to those of Short and Cauraugh (1997, Experiment 1), who also used a random presentation of target locations, albeit with the #9 target standardized to each participant's right shoulder height. Reference to their findings is estimated from their Figure 2 (Short & Cauraugh, 1997, p. 140).

Results from our right-hand random condition appear to be qualitatively similar to Short and Cauraugh's (1997) findings. Specifically, when the task was to bring the left end of the dowel to the lower targets or the right end of the dowel to the higher targets, most participants picked up the dowel with an overhand grip. Conversely, when the task was to bring the left end of the dowel to the higher targets or the right end of the dowel to the lower targets, the preference was to use an underhand grip. These results are consistent with the desire to maximize end-state comfort. One finding in the present study differed from Short and Cauraugh's (1997) results. They found a very strong point-of-change effect between Target #7 and 8, where participants clearly switched to the opposite grip. By contrast, the decision to switch grips with the right hand was not as dramatic among our participants, as can be seen in Figure 3. Thus, we did not find a distinct point-of-change effect, which may possibly be attributed to the normalized height of the #9 target in their study but not ours.

Posture-Based Motion Planning

It is certainly possible that the increased complexity of the bimanual condition changes the entire nature of the task, in that the planning process at each target location must consider four possible grip configurations, as opposed to only two for the unimanual task. That is, with only one dowel to transport with the right hand, participants make a binary decision: overhand grip or underhand grip. The bimanual task presents the participant with four options: (a) left and right overhand, (b) left and right underhand, (c) left overhand and right underhand, and (d) left underhand and right overhand. According to a posture-based motion-planning model (e.g., Rosenbaum, Meulenbroek, & Vaughan, 2001; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001), one of the most important aspects of motion planning is establishing a *constraint hierarchy*, which is "a set of prioritized requirements defining the task to be performed" (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001, p. 709). If we assume that the highest level constraint here is to minimize awkward final postures (i.e., maximize end-state comfort), then all possible initial grip configurations, available as stored postures, are evaluated as to how well they satisfy this constraint. For bringing the end of the dowels to the highest targets, using opposite grips with each hand is the only posture that satisfies the end-state comfort constraint. The fact that not all participants showed the opposite-grip effect for the highest targets suggests at least three possibilities. One is that there are large individual differences in the perception of end-state comfort as a posture constraint. Some people may be more willing to tolerate awkward postures than are others. Also, it is possible that the preference for end-state comfort could be weighted differently for each hand. In future work, the application of verbal protocol analysis (e.g., Ericsson & Simon, 1984) could be a useful tool for discerning the specific perception-action problem solving steps adopted by participants. Another possibility is that participants may have not allowed sufficient time to evaluate the posture store before selecting their initial grip, although the task was self-paced and there was no pressure to move quickly. It might be interesting to change the self-paced nature of the task to more of a reaction time, speeded-movement paradigm, which could provide more information about the difficulties inherent in the planning and selection process (see Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992, for an example of chronometric measures used with unimanual reaching tasks).

Using opposite grips with each hand is also the optimum posture for maximizing end-state comfort when bringing the end of the dowels to the lowest targets. But again, not all participants adopted this grip configuration. Here, however, the instruction to "bend at the knees" for the lower targets changes the dynamics of the task. If participants considered the "bending-the-knees" posture as the goal posture for the lowest targets, then the choice of initial grips takes on less importance, at least in terms of perceived comfort, because adjustments can be made on the fly. Such a strategy was evident in the right end ascending sequence in Experiment 1, but certainly could have been an option in the other conditions. Further study of this planning strategy is warranted. We suggest that future research either control for knee joint movement or systematically analyze knee flexion-extension to better evaluate the perception of how comfortable the arm will feel at the end of the movement.

As a final point, we have interpreted our findings as consistent with the concept of constraint hierarchies within a posture-based model of motion planning. However, we acknowledge that our findings are also consistent with an abstract level of description afforded by nonlinear dynamic pattern theory (see Wallace, 1996, for an introduction to this perspective). For example, the strong opposite-grip effect at the extreme target locations could be interpreted in terms of an intrinsic stability for certain relative grip postures; the performance differences depending on whether the targets were tested in an ascending or descending order may indicate the potential presence of hysteresis; and the moderate point-of-change effect could be interpreted as a type of phase transition. A challenge for future research is to determine whether one level of description provides greater explanatory power than the other.

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Authors' Notes

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