The Pennsylvania State University

The Graduate School

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COGNITIVE HEURISTICS CAN BE MORE IMPORTANT THAN BIOMECHANICS IN HUMAN ACTION PLANNING: THE NEAR OBJECT EFFECT IN WALKING AND REACHING

A Thesis in

Psychology

by

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Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

August 2012

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ABSTRACT

The coordination of walking and reaching has received remarkably little attention in the study of motor control. Among the few studies that have been done on this topic, very few have explored macroscopic decision-making about walking-and-reaching paths. To shed light on this topic, I asked participants to choose between picking up a bucket on the left and picking up a bucket on the right to carry the picked-up bucket to a left or right platform equally far (16 feet) from the participant's starting position. The left and right buckets stood 2 feet, 4 feet, 6 feet, or 8 feet from the participant's starting position and were tested in all possible combinations. In Experiment 1-3, I found that participants did something surprising: When the two buckets were different distances from the starting position, participants picked up the nearer bucket even though that meant they had to carry it farther. This result held up regardless of whether the bucket was light or heavy (even as heavy as 7 lbs). In Experiment 4, I reversed the bucket locations to the second half of the walking path, so the buckets stood 2 feet, 4 feet, 6 feet, or 8 feet away from the ending position, not the starting position. With this arrangement, I found that the number of participants who chose the near bucket did not exceed the number of participants who chose the far bucket, in contrast to what I found in Experiments 1, 2 and 3, where there was a strong near-bucket preference. In Experiment 5, I found that participants picked up the near bucket to minimize pre-lift distance rather than to maximize post-lift distance. Collectively, these results suggest that some cognitive factor was taken into account that offset the cost of carrying the bucket farther. More broadly, the results indicate that a simple view of biomechanical cost reduction for action selection is insufficient. Cognitive factors must also be taken into account.

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ACKNOWLEDGEMENTS

I thank my advisor, David Rosenbaum, for his help with and support of this work, and I thank the two other members of the thesis committee, Ping Li and Janet van Hell, for their very useful suggestions. I also thank the two other graduate students in our lab, Kate Chapman and Chase Coelho, as well as visiting scholar Oliver Herbort, and post-doc student Bree Studenka for their kind suggestions on the experiments. Michael Abate, Jamie Beckett, Brandi Ithal, Yidi Li, Anita Remizova-Volfson, Kelly Sager, Elisabeth Paulson, Sarah Snyder, and Lisai Zhang helped with data collection. Their assistance is gratefully acknowledged.

CHAPTER 1

INTRODUCTION

How are movements selected? How do people choose particular movements rather than the other movements that are possible to achieve a task? What standards, explicit or (more likely) implicit, are used in movement selection? This thesis is concerned with these questions.

In the Introduction I will review some approaches that have been taken to the question of whether movements are optimal with respect to biomechanics, followed by a discussion of previous research on the coordination of reaching and walking, the domain in which the optimization question is pursued here. Then I will turn to a series of experiments that bear on the optimization question and, interestingly, yield a new phenomenon that holds great interest, not just for motor control but also for cognitive science more generally.

Optimality In Motor Control

One way of addressing the question of whether motor control is optimal is to consider the degrees of freedom problem for motor control. This problem was introduced by the Russian physiologist Nicolai Bernstein (1967), who noticed that the human body has more degrees of freedom than are strictly needed to achieve most tasks. The extra degrees of freedom enable the system to flexibly control movements under different conditions. Therefore, the system needs to work out a way to reduce the degrees of freedom to select a given movement.

A dominant approach to the solution of the degrees of freedom problem lies in how “optimal” the generated movements are. Pursuing this idea, researchers have studied the kinematic and kinetic properties of movement trajectories. Researchers have proposed different theories to describe what criteria might be used to generate (or might characterize) optimal movements.

An influential idea came from Hogan and Flash (1987), who proposed that point-to-point movements are generated in a way that minimizes mean squared jerk (the mean of the squared values of the time derivative of acceleration) or, equivalently, that maximizes smoothness. The tangential velocity profiles of such movements are bell-shaped.

The "minimum jerk" theory of Hogan and Flash emphasized kinematic features of reaching movements. Kinematics is the description of positions in time without regard to forces or torques. Another group later suggested that reaching movements are characterized not by minimum jerk but instead by minimum mean squared torque change (Uno, Kawato & Suzuki, 1989). These authors suggested that the sum of squared torque change, an energetic variable, is minimized. Their "minimum torque change" model therefore emphasized kinetics rather than kinematics. Kinetics is the description of positions in time with regard to forces or torques, not without regard to forces or torques.

Yet another view, from Sparrow and Newell (1998), held that generated movement patterns minimize metabolic energy. Minimizing metabolic energy would result in the most efficient movement possible, according to these authors.

Turning to another approach, feedback control theory, Todorov and Jordan (2002) proposed that what is optimized in movement is the feedback control used to ensure successful task completion. Optimizing feedback control helps reduce biomechanical variability and inefficiency, these authors said.

As this short review indicates, there have been several optimization theories of movement control. However, no optimization theory has proven to be optimal in the sense that none of them fully accounts for all the data. Most importantly, there are notable sub-optimalities in motor control, as described next.

Biomechanical Sub-Optimality In Motor Control

The models reviewed above try to find some single biomechanical factor that is optimized. However, it is questionable whether motor control is actually optimized biomechanically. If it is not, the quest for a single biomechanical factor for optimization of movements might be misguided.

Consider a study by Jax and Rosenbaum (2007). Here participants were asked to look at a virtual display and to aim from a center home location to whichever one of several peripheral targets appeared, and next to move back to the home location. In some trials, an obstacle stood between the center and the target. Participants were expected to circumvent the obstacle. In other trials, there was no obstacle in the way. It was found, surprisingly, that participants made needlessly curved movements in trials where no obstacle appeared but where an obstacle had recently appeared. The results showed that participants were primed by the hand path of the previous trials. This *hand path priming* effect, as Jax and Rosenbaum called it, would not be predicted by a biomechanical optimization approach, as was noted in a review of such models by two proponents of that approach (Shadmehr & Krakauer, 2008).

A subsequent study found the same hand path priming effect in a real rather than virtual action task (van der Wel et al., 2007). Here participants were asked to hold a dowel upright and tap its base on one target after another in time with a metronome. The targets were arranged in a semi-circle on a table top. As in the study of Jax and Rosenbaum (2007), in one condition there was no obstacle between targets, but in another condition, an obstacle stood between two of the targets. Participants had to raise their hand higher to pass over the obstacle. The participants generated higher hand paths than necessary in the tapping movements following the obstacle, even though no obstacle stood between the targets where the extra high arcs were displayed. This hand path priming effect was not merely an artifact of muscle contraction or some other peripheral neuro-muscular artifact because the effect was also found when participants moved one hand over the obstacle and continued the tapping with the other hand. Therefore, this study, like the one by Jax and Rosenbaum (2007), suggested that movements are not simply made in a way that optimizes biomechanics. Some procedural priming also played a role.

Heuristics In Motor Decision Making

The last section was called *Biomechanical sub-optimality in motor control*, but the fact that motor control is *biomechanically* sub-optimal does not imply that it is *cognitively* suboptimal. This contrast brings to mind the famous Nobel Prize winning research of Amos Tversky and Daniel Kahneman (1974), who showed that people often use simple, quick heuristics in in everyday decision making, As these researchers showed, people often behave sub-optimally from an economic standpoint.

Is it reasonable to think that heuristically based decision making also applies to motor control? The findings of Jax and Rosenbaum (2007) and van der Wel et al (2007) suggest at the empirical level that it does. But why *in principle* is this possibility reasonable? At least four reasons can be given.

First, psychological, cognitive factors could come into play in movement decision making. It is hard to circumvent cognitive processes when movement tasks are complex or, for that matter, simple. For example, the instructions given to participants could change their behavior, suggesting that different mental processes are going on. Thus, cognitively biased heuristics may interact in movement tasks. Biomechanical optimality theories do not generally consider the influence of psychological factors such as instructions. Second, planning for biomechanically optimal movement is computationally costly. Heuristically based action planning is more economical (Simon, 1955). Third, optimal behavior might not be achievable all the time but heuristically based movements might be more likely to be. Fourth, compared to optimality theory, heuristically based motor decision-making allows for the possibility of individual differences in movement selection. People with similar biomechanical makeups could nevertheless rely on heuristics that cause them to adopt different strategies for completing tasks. As will be seen later, this turns out to be an important feature of the tasks reported here. Biomechanical optimization would not predict individual differences on the scale to be reported here.

The Coordination Of Walking And Reaching

Do heuristics lead to movement selections only when the movements are completed quickly, as in hand movements around obstacles, or do they also lead to movement selections when the movements are completed slowly, as in walking down one path or another to pick up and carry an object? The cost of biomechanically suboptimal performance would be much greater in the latter case than the former, which means that if heuristics were found to play a role in choosing walking and reaching paths, and if the chosen walking-and-reaching paths were much more biomechanically costly than the unchosen walking-and-reaching paths, that would be a striking outcome. Exactly that striking outcome will be reported here. On the way to presenting that result, I summarize two recent experiments in our lab that set the stage for the present work following some more general comment about walking and reaching.

The coordination of walking (locomotion) and reaching (prehension) is very common in everyday life. We coordinate our hands and feet to reach for a cup on a table several feet away or to grab an item on a shelf when walking down the aisle of a grocery store. However, walking and reaching is not a well-studied topic in motor control, even though there are a great many studies of walking alone and of reaching alone.

The argument that walking and reaching should be regarded as coordinated motor activities rather than as separate motor activities was made before by Georgopoulos and Grillner (1989), who provided various lines of evolutionary and neural evidence to suggest that reaching evolved from locomotion and share similar neural circuits with locomotion.

Later, several researchers studied how walking and reaching are coordinated. They explored the kinematic and kinetic features of walking and reaching tasks. Cockell, Carnahan, and McFadyen (1995) compared walking alone with walking plus picking up a small or large object. Cockell, Carnahan, and McFadyen found that in walking and reaching tasks, participants altered the normal pattern of arm swinging relative to leg swinging at the time of reaching. During normal walking, the contralateral arm and leg swing in phase while the ipsilateral arm and leg swing in anti-phase. Cockell, Carnahan, and McFadyen found that at the time of reaching, this phase relation was reversed. The limb accomplishing the phase reversal was the arm rather than the leg.

Following this first study, Carnahan, McFadyen, Cockell, and Halverson (1996) analyzed the detailed kinematics and EMGs associated with the same experimental tasks. Consistent with the earlier results from this laboratory, this group of researchers found that the arm and wrist kinematics in walking with or without reaching were significantly different, but the lower limb kinematics were almost the same. Based on these findings, Carnahan, McFadyen, Cockell, and

Halverson inferred that the control of upper limbs and lower limbs are hierarchical. The lower limbs are controlled in a way that does not depend on the way the upper limbs are used, but the way the upper limbs are controlled depends on the nature of the reaching task.

Whereas Carnahan et al. suggested that the legs are superordinate to the arm in motor control, Bertram, Marteniuk, and Wymer (1999) reached a different conclusion. They found that participants walked more slowly when transporting an *uncovered* cup to a target than when transporting a *covered* cup to the same target. Their measure of walking speed was chest velocity rather than leg kinematics per se; that is, their measure was how quickly the chest (or torso) moved forward in the environment. The fact that the trunk moved more slowly in the difficult (easy-to-spill) conditions than in the easy (hard-to-spill) conditions suggests that lower limb control is not always independent of manual control. This conclusion was further supported through another manipulation used by Bertram, Marteniuk, and Wymer -- varying the size of the target to which the cup was carried.

In a follow-up study, Bertram, Marteniuk and Mackey (2000) used a more demanding task. They asked participants to walk to reach for a cup and then to transport it as quickly as possible to a target without spilling the water. Going as quickly as possible was not a requirement in the earlier study of Bertram, Marteniuk, and Wymer (1999). Bertram, Marteniuk and Mackey found that participants elongated their stance phrase at the time of picking up the cup if the cup was uncovered, but they did not elongate their stance phase as much if the cup was covered. Based on this result, Bertram, Marteniuk and Mackey concluded that adding complexity to the task for both upper and lower limb caused the lower limb as well as the upper limb to make adjustments.

The studies of Carnahan et al. and of Bertram et al. focused on the coordination of locomotion and prehension at the time of reaching or when the object was transported to be put down. However, aspects of the coordination could have been planned in advance, before the object was reached. In support of this possibility, van der Wel and Rosenbaum (2007) found that long before reaching an object, lower limb movements are adjusted to accommodate different oncoming prehension tasks. In the study of van der Wel and Rosenbaum, participants walked several steps toward a table, picked up a standing plunger on the table, and transported it to the left or to the right, either over a short distance or over a long distance. van der Wel and Rosenbaum found that prior to long-distance object transports, participants varied their stride lengths while walking toward the table to permit standing on the left foot if the oncoming lateral transport was far to the right or to permit standing on the right foot if the oncoming transport was far to the left. The anticipatory effect discovered by van der Wel and Rosenbaum shows that the legs can indeed change their behavior for reaching and can do so well in advance of the reaching.

Another line of research on walking and reaching sets the stage for the study reported here (Rosenbaum, 2008; Rosenbaum, Brach and Semenov, 2011). The experimental paradigm used in this other line of research relied on a two-alternative choice method. Participants were given two sets of action choices differing with respect to two dimensions – how far participants had to walk, and how far participants had to lean over to pick up an object (a child’s beach bucket) to be carried to some target site. The task and setups of the two studies were similar. Participants were asked to choose a left or right path. Both paths required the participant to walk and pick up a bucket on a table several steps away from the starting point, and then to walk to put the bucket down on a far location. In both studies, the bucket was placed on the left, right, or middle of a near table which participants had to pass on the left or right to pick up the bucket on the way to the far location. As a result, choosing the left or right walking path resulted in different degrees of leaning for the reach to the bucket. Rosenbaum (2008) crossed this factor with the lateral position of the far location – namely, how far to the left or right it was. Rosenbaum, Brach and Semenov (2011) varied how far either of two targets was from the far end of a table on which stood a single bucket whose horizontal position changed. Therefore, the study of Rosenbaum, Brach, and Semenov (2011), like the study of Rosenbaum (2008), pitted reaching (leaning) distance against walking distance. The question in both studies was, Which mattered more, walking distance or reaching (leaning) distance? The answer in both studies was the same. Participants preferred to walk more to reach (or lean) less. The most important implication of these studies for the new work to be presented here is that they established a methodological framework and theoretical background for my master's thesis research.

Individual Strategies In Completing Movement Tasks

As mentioned earlier, individual differences in movement planning and selection can shed light on the means by which movements are planned and selected. If different people do the same task in very different ways, it is hard to reconcile that result with the hypothesis that biomechanical optimization governs their task-completion methods. Apples falling to the earth do not do so in different ways depending on their individual characteristics. Individual differences are easier to reconcile with the hypothesis that heuristics play a role in action selection.

Consistent with the idea that people use heuristics rather than being locked into the optimization of biomechanical variables, it has been found that different people adopt different strategies to complete the same movement goal. To take a familiar example, left-handed people are more likely to use the left hand than the right hand to reach for a mug, while right-handed people do the reverse. Handedness is not a simple biomechanical difference, however, at least as far as is known in the handedness literature.

It would be useful to know that there are individual differences in the strategies that people use for action tasks other than, or in addition to, those related to handedness. A study by Rosenbaum, Coelho, Rhode, and Santamaria (2010) helped address this need. They found individual strategies in a sequential stacking task where participants were asked to stack Tupperwear® containers that were laid out on a table. The participants were supposed to place the stack on a location at the end of the table. Different participants adopted different strategies, but more interestingly, each participant consistently used his or her own strategy across all the trials of the experiment.

These consistent individual differences fit better with the idea of heuristically based decision-making for action rather than biomechanically determined optimization. It is possible that different heuristics are adopted by different people based on their individual inclinations. The decisions participants make could draw upon their different prior experiences and their different cognitive information processing of the task environment. In the present study, individual differences likewise emerged.

Current Study

The tasks reviewed in the last two sections were somewhat complicated. They required leaning over a table to pick up and carry an object to a remote location, or picking up a series of objects laid out on a table to form a stack at one end of the table. In the present study, I used a much simpler task -- one that I thought might shed light in an even more direct way on the relative contributions of cognition and biomechanics in action planning. The task involved nothing more than deciding whether to pick up a child’s beach bucket on a left platform or on a right platform to carry the picked-up bucket to a farther left or right platform, respectively. The range of tasks that I used is shown in Figure 2-1.

I investigated the influence of two main factors in this simple situation: the distance from the starting point to the pick-up position of the left or right bucket (the “pre-lift” distance), and the distance from the pick-up position to the far location where the lifted bucket would be put down (the “post-lift” or “transport” distance). The empirical question was straightforward: Would participants pick up the near bucket and carry it far or would they pick up the far bucket and carry it near? In other words, would the pre-lift phase or the post-lift phase be judged more costly?

From the perspective of physical effort, transporting an object over a longer distance is clearly less desirable than transporting an object over a longer distance. More physical work must be done in the former case than in the latter. Work, it will be recalled from physics, equals force multiplied by the distance over which the force is applied. The relative benefit of picking up a far object and carrying it a shorter distance is especially pronounced, therefore, if the weight of the transported object is great. In that case, minimizing the transport distance is especially important. From the standpoint of biomechanical optimization, the obvious choice is to pick up a far bucket, not a near bucket, especially if the buckets are heavy.

Is it possible that participants would violate biomechanical optimization in this very simple task? Owing to the simplicity of the task, it would be surprising if they did. However, there are several reasons why they might, and all of them expressible as cognitive heuristics.

First, picking up the closer object could reduce uncertainty. There would be greater uncertainty about the exact position of the far object than the near object. If reducing uncertainty were an important consideration, participants might opt for the near bucket rather than the far bucket.

Second, working memory load could be reduced by picking up the near bucket rather than the far bucket. By completing the picking-up action earlier rather than later, the working memory load of this part of the task could be reduced sooner rather than later. This speculation is supported by the finding that maintaining goals and subgoals taxes working memory (Kane & Engel, 2003). If reducing working-memory load is an important objective, participants might pick up the near bucket rather than the far bucket even if this increases physical work.

A third reason why the near bucket might be picked up despite the greater carrying distance it incurs is that the near object might attract more attention than the far object. Either by virtue of its larger size, its greater proximity, or its greater perceptual "pull" on the manual prehension system, the closer object might be seen as a stronger candidate for picking up and carrying, and so might be favored.

One or more of these heuristics could operate; they are not mutually exclusive. They are introduced here to show that, were I to find that participants pick up the near bucket and carry it far, that result might be explainable even if it were surprising.

A final remark, which is possibly anti-climactic at this stage of the presentation, is there is the intriguing possibility that there will be individual differences in this task. Some people might always choose the close bucket; others might always choose the far bucket. Some people might always use the right hand; others might always use the left hand. If these individual differences emerge, they might not be correlated with simple physical features of the participants such as their height or weight. The less identifiable the physical basis for the individual differences, the "more psychological" they could be said to be.

CHAPTER 2

EXPERIMENTS 1- 3

Method

In each experiment, 27 Pennsylvania State University students participated for course credit. The age of the participants ranged from 18 to 25 years. As assessed by a short form of the Edinburgh handedness inventory (Oldfield, 1971), in Experiment 1, 24 of the 27 participants were right-handed. Among those who were not, two were left-handed and the other one was ambidextrous. In Experiment 2, 26 participants were right-handed and one was ambidextrous. In Experiment 3, all 27 participants were right-handed. None of the participants reported neurological deficits. All had normal or correct-to-normal vision. All three experiments were approved by the Penn State Institutional Review Board, and informed written consent was obtained from each participant.

The setup for Experiment 1-3 is shown diagrammatically and from a bird's-eye perspective in Figure 2-1. Photographs of two of the setups are shown in Figure 2-2.

In each trial, the participant stood at the horizontal line of the T on the floor, with his or her toes just touching that line and with his or her two feet straddling the T's stem. Standing here, the participant looked out at four platforms, two to the left, one near and one far, and two to the right, one near and one far. The two far platforms were the same distance from the starting line in all conditions (16 feet).

Each platform had a round top (8.5 inch radius) and a smaller round base (6 inch radius). All the platforms were 2 feet 6 inches high, which is at about hip level for a typical, 62 inch tall adult.

The platforms on the left and the platforms on the right straddled an imaginary line extending straight from the stem of the T. The distance of each platform center to the imaginary line was 1.5 feet. The distance from the center of the left or right table on either side of the imaginary line was about 3 feet. The aisle between the platforms was 18 inches wide, from rim to rim of the left and right table tops. This width of the aisle, along with the height of the platform, enabled participants to walk along with very little leaning to reach for either bucket. The hip width of a typical adult is less than 18 inches.

The tables on the left and right were arranged so the distances from the horizontal start line to the two far tables were always the same, 16 feet. The positions of the two near tables varied between trials could be 2, 4, 6, or 8 feet from the start line. Thus there were 16 combinations for the left and right close table locations, comprising the 16 conditions tested for each experiment. For four of these 16 trials, the left and right close tables were equidistant from the start position.

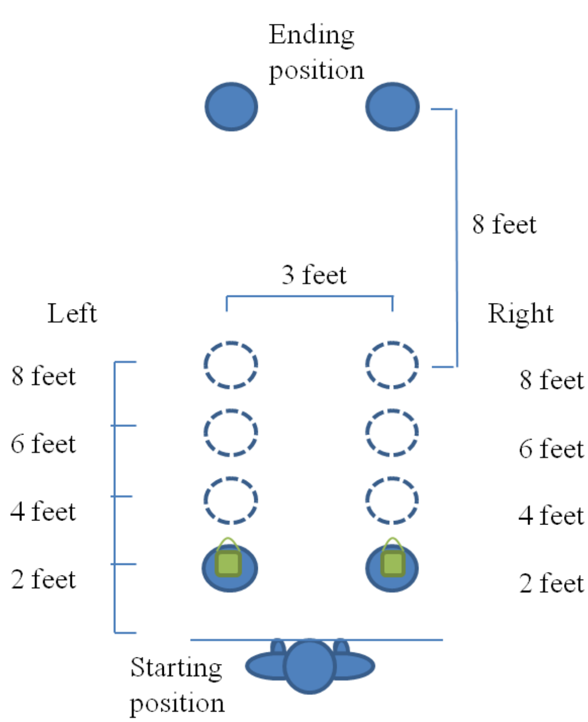

Figure 2-1. Setup for Experiments 1-3.

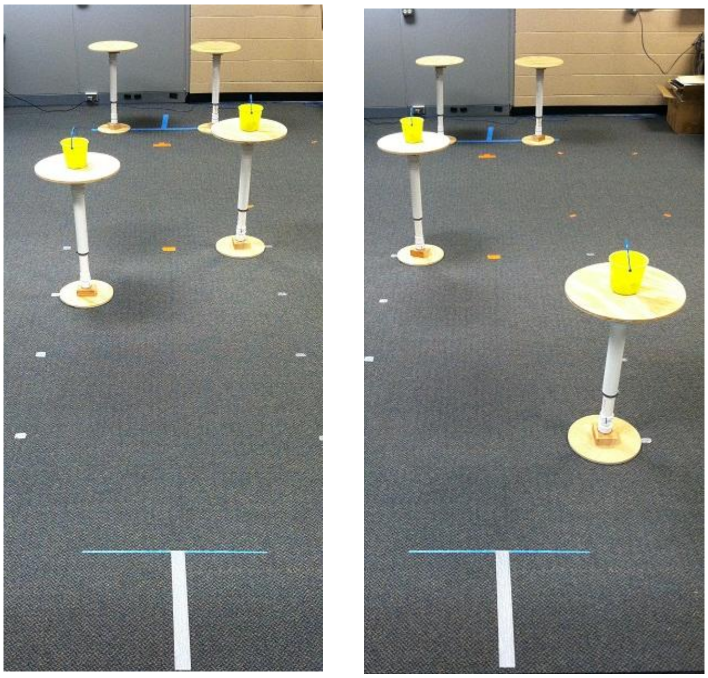

Figure 2-2. Photographs of two of the conditions of Experiments 1-3.

On each of the two close tables, a light green plastic child's beach bucket stood on the center of the table top. The bucket's blue handle stood upright and was set parallel to the walking path. The dimensions of the buckets, which were purchased from Target® in State College, PA, were as follows. The diameter of the base was 10 cm. The diameter of the top was 13.7 cm. The height of the bucket was 12.4 cm. The height of the bucket handle when it stood up was 7.6 cm about the top of the bucket.

The instruction to the participant was to stand at the starting position, look at the setup, and take a brief moment to choose between the two action alternatives according to whichever one seemed easier. One choice was to walk and grasp the handle of the bucket on the left with the left hand and carry that bucket to the left far table. The other choice was to walk and grasp the handle of the bucket on the right with the right hand and carry that bucket to the right far table. Participants were asked to walk and reach for the bucket without stopping. They were also asked, after putting the bucket on the far table, to walk back to the starting position and once there, to remain facing away from the platforms until the experimenters set up the platforms and buckets for the next trial, whereupon she asked the participant to turn around and take a moment before choosing whichever walking-and-reaching task seemed easier in the next trial.

Each participant went through 16 experimental trials, reflecting all 16 possible combinations of the left and right near platform locations. The 16 conditions were tested in a random order for each participant. The experimental trials were preceded by 2 practice trials for participants to familiarize with the task. To compare walking and reaching behavior with the walking baseline in future analyses, a walking-without-grasping trial was added to the beginning and the end of the experiment. Here participants were asked to walk naturally to the far table without lifting a bucket. The platforms and buckets were moved away for this first task. Throughout the experiment, participants were videotaped and duct tape patches were put on their wrists and feet as markers, to allow for possible kinematic data analysis later if needed.

In Experiment 1, the buckets were empty. In Experiment 2, the buckets were filled with 12 penny rolls weighing 3.5 lbs. In Experiment 3, the number of penny rolls was doubled to 24 per bucket, bringing the weight up to 7.0 lbs.

Results

Near Bucket Effect

For Experiment 1-3, the mean number of trials in which participants chose a near bucket, and the mean number of trials in which participants chose a far bucket (just the complement of the first number) are plotted in Figure 2-3. One sample t-tests indicated that the mean number of close-bucket trials was larger than 6 in all three experiments (in Experiment 1 $t=3.5$, $p<0.01$; in Experiment 2, $t=2.45$, $p<0.05$; in Experiment 3 $t=4.19$, $p<0.001$). This result indicates that participants picked up the close bucket more than would have been expected by chance alone (half of the 12 non-equidistant trials) in all three experiments. An ANOVA showed that the close-bucket preference did not change over experiments ($F= 0.36$, $p=0.699$).

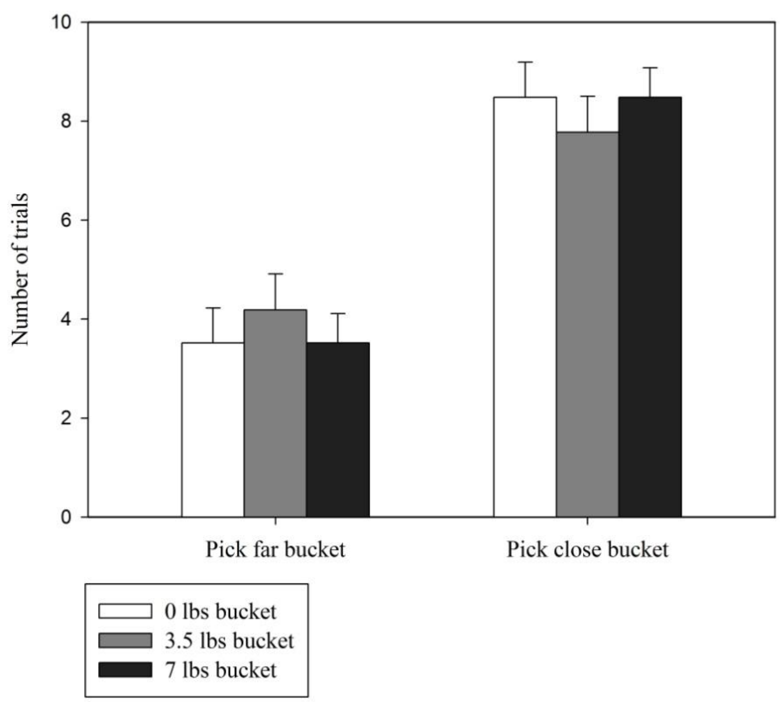

Figure 2-3. Mean number of trials in which participants chose the far bucket (left bars) or the close bucket (right bars) in Experiment 1 (bucket load = 0 lbs), Experiment 2 (bucket load = 3.5

lbs), and Experiment 3 (bucket load = 7 lbs). The error bars indicate +1 standard error of the mean for the 27 participants in each experiment.

Right Hand Bias

Figure 2-4 shows the average number of trials in which participants chose the left or right bucket in Experiments 1-3. The average number of trials in which the right bucket was chosen was significantly larger than the number that would be expected by chance (i.e. 8 trials out of the 16 trials in which left-versus-right-hand choices could be made; one sample t-test, Experiment 1 $t=3.88$, Experiment 2 $t=5.65$, Experiment 3 $t=7.31$, $p \le 0.001$ in all three experiments). Thus, it can be seen that there was a strong right bias, presumably reflecting a bias to use the right hand. Although it appears that the right bias increased with the weight of buckets, this trend was not statistically significant ($F= 1.02$, $p>0.1$).

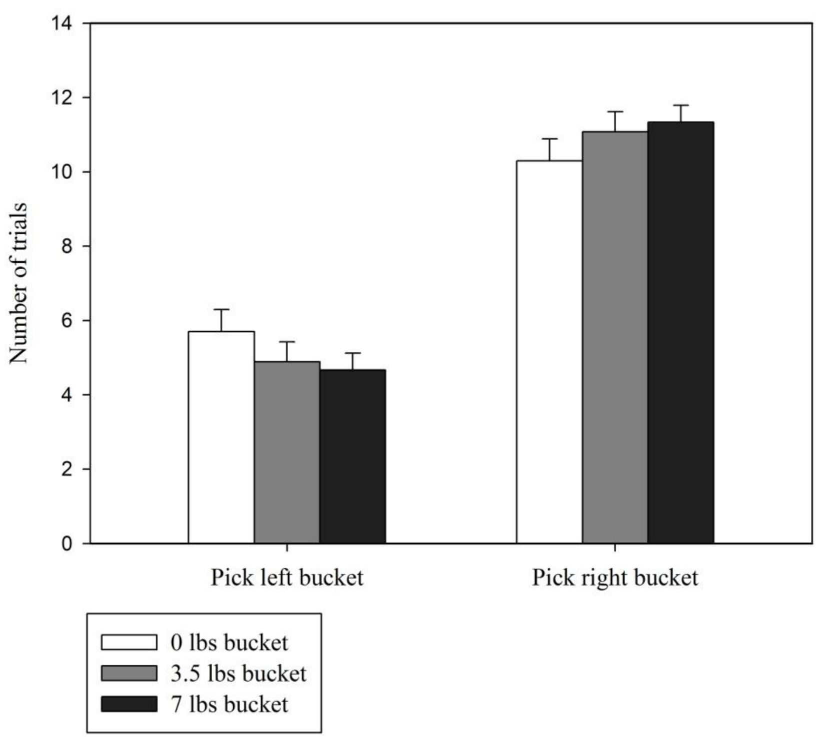

Figure 2-4. Mean number of trials in which participants chose the left bucket (left bars) or the right bucket (right bars) in in Experiment 1 (bucket load = 0 lbs), Experiment 2 (bucket load = 3.5 pounds lbs), and Experiment 3 (bucket load = 7 lbs). The error bars indicate +1 standard error of the mean for the 27 participants in each experiment.

Perhaps it is not surprising that there was a right bias because nearly all the participants were right-handed. However, it is important to point out that the right bias in these three experiments was independent of the near-object effect, for the near bucket choices were distributed equally among the right-side and left-side choices, and vice versa. It is also worth noting that when the left and right buckets were equi-distant from the start position, almost all participants chose the right bucket, but when the left and right buckets were not equi-distant from the start position, fewer participants chose the right bucket. In Experiment 1 the proportion of participants choosing the right bucket in the 4 equi-distant trials was .88, while the proportion of participants choosing the right bucket in the 12 different-distant trials was 0.57. In Experiment 2 the corresponding proportions were .86 and .64. In Experiment 3, the corresponding proportions were .86 and .66.

Other Strategies

Picking up the near bucket or picking up the bucket with the right hand can be viewed as two strategies or, if you will, two heuristics. To investigate whether participants adopted other strategies, and to compare those other strategies with the two strategies already considered – the near-bucket strategy and the right-bucket strategy – I identified participants who picked up the near bucket or the far bucket in at least 9 trials, which is the smallest number of trials that could be considered significantly different from chance alone (6 trials out of the 12 trials in which the left and right buckets had different distances from the participant's start position). The relevant values are shown in Table 2-1. Note that the close bucket strategy and the far bucket strategy are mutually exclusive, as are the right hand strategy and the left hand strategy.

Table 2-1. Number of participants out of 27 in Experiment 1 (bucket load = 0 lbs), Experiment 2 (bucket load = 3.5 lbs), and Experiment 3 (bucket load = 7 lbs) who adopted the near bucket strategy (Near), the far bucket strategy (Far), the right hand strategy (Right), the left hand strategy (Left), or no consistent strategy (None) in the 12 trials in which the left and right buckets were at different distances from the start position.

Experiment	Near	Far	Right	Left	None
1	17	3	4	1	2
2	13	3	6	0	5
3	16	3	5	0	3

A Chi-square test showed that the rows and columns in this table are independent: Chi-square = 2.35, df = 6, p= 0.89. In doing this Chi-square test, I eliminated the Left strategy values because the counts in these cells were so small that they did not meet the requirement of Chi-square approximation. What the test shows is that the number of participants using each strategy did not change across these three studies or, said differently, did not change as a function of bucket weight. Clearly, the near bucket strategy was the one that was used most consistently.

Choices and Relative Proximities

Figures 2-5 through 2-13 provide a closer look at the relation between participants' choices and the relative proximities of the buckets. These figures show the probabilities (pooled over participants) of lifting the right bucket as a function of the pre-lift right-bucket distance minus the pre-lift left-bucket distance. The data are shown separately for Experiments 1, 2, and 3 (bucket loads of 0 lbs, 3.5 lbs and 7 lbs, respectively). In each graph, the dots on the left are for the conditions in which the right bucket was closer, and the dots on the right are for the conditions in which the left bucket was closer. The triangles represent the equal left/right distance conditions. Note that some dots are overlapped in these graphs. In fact in each graph there are six dots on the left and six dots on the right because there are six conditions in which the right bucket is closer than the left bucket and six trials in which the right bucket is farther than left bucket.

It can be seen that in all three experiments, the graphs from all participants show a general close bucket effect trend. When the right bucket is closer than the left bucket, which is when the right bucket distance minus the left bucket distance is negative, participants preferred the right bucket, so p(R) was high. When the right bucket was farther, p(R) was low.

In the graphs that follow, the data are shown separately for participants who could be assigned either to a close-bucket or far-bucket strategy. Different patterns emerge for these two groups. Close-bucket strategy participants preferred the right bucket when the right bucket was closer than the far bucket. Far-bucket strategy participants showed the opposite pattern.

To review in more detail what these graphs show, they reveal the following. Figure 2-5 through Figure 2-7 show the probability, p(R), of lifting the right bucket under different right and left bucket distance differences (right distance minus left distance) in the 0 lbs bucket load study. In these figures, the dots indicate 12 conditions of unequal position trials. The triangles represent 4 equal position trials.

Figure 2-5 shows the average p(R) of all participants. A general close-bucket preference of all participants is observed in this figure. Figure 2-6 shows the average p(R) of close-bucket strategy participants, and Figure 2-7 shows the average p(R) of far-bucket strategy participants. Figure 2-6 shows the preference of close bucket in close bucket strategy participants, and Figure 2-7 shows preference of far bucket in far bucket strategy participants.

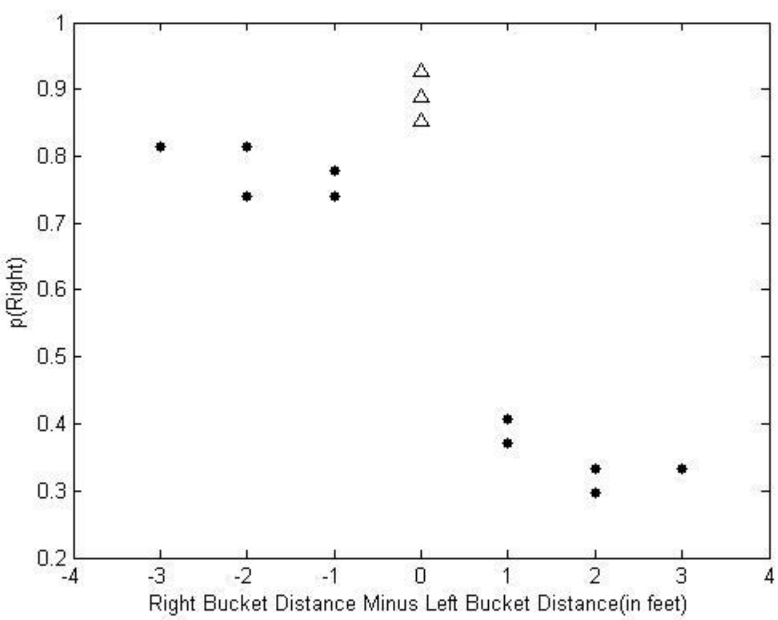

Figure 2-5. Proportion, p(R), of all participants choosing right hand in each condition in Experiment 1 (0 lbs bucket). In the graph, the left half dots indicate the conditions when right bucket is closer, and the right half dots indicate the conditions when left bucket is closer. The

triangles represent the conditions with equal left/right distance. The graph shows a preference of picking up close bucket in general.

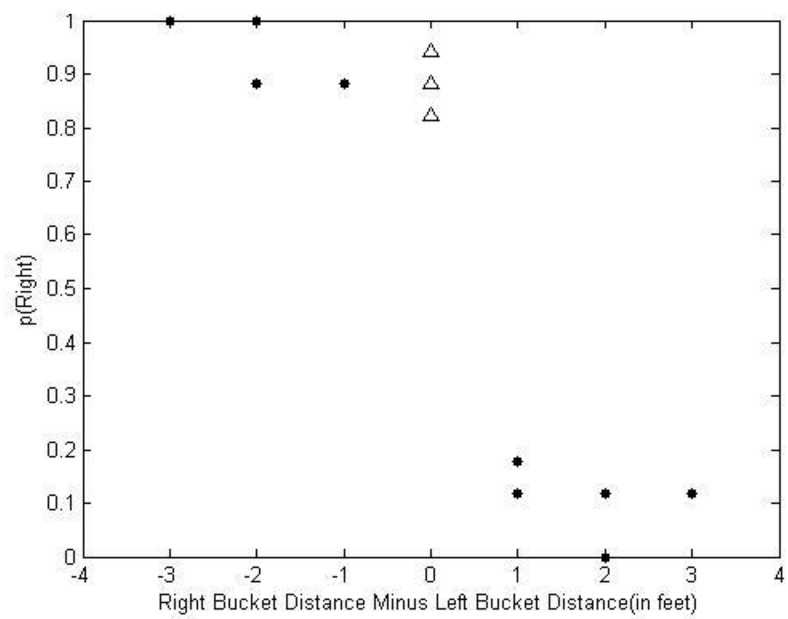

Figure 2-6. p(R) for the 17 close-bucket strategy participants in Experiment 1. The graph shows the clear trend of picking up close bucket for close bucket strategy participants.

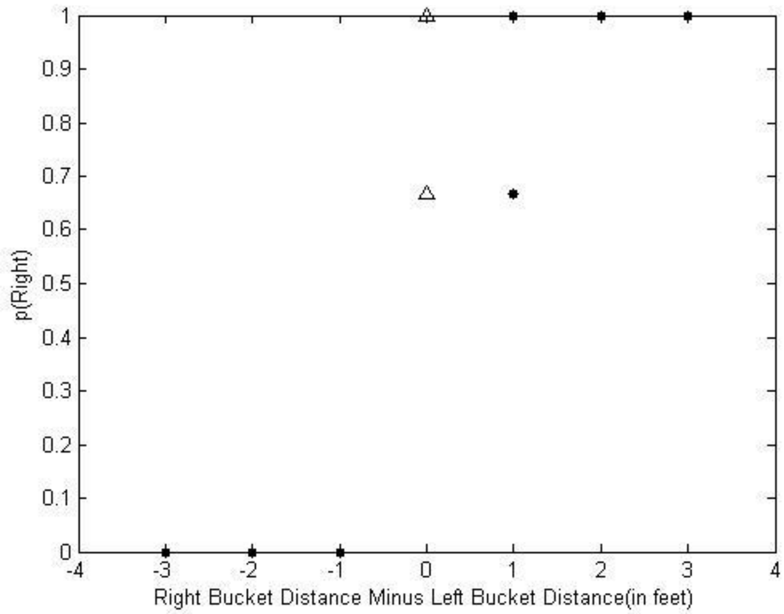

Figure 2-7. p(R) for the 3 far-bucket strategy participants in Experiment 1. The far-bucket strategy participants showed a clear opposite pattern compared to the close-bucket strategy participants.

Figure 2-8 through Figure 2-10 show the probability, p(R), of lifting the right bucket under different right and left bucket distance differences (right distance minus left distance) in the 3.5 lbs bucket weight experiment (Experiment 2). The patterns of these graphs are the same as those in Experiment 1. In general, participants preferred the close bucket. Then, plotting the data separately for close-bucket strategy participants and for far-bucket strategy participants, one sees a systematic effect of the relative distances of the left and right buckets for the two groups, but in opposite directions for the two groups.

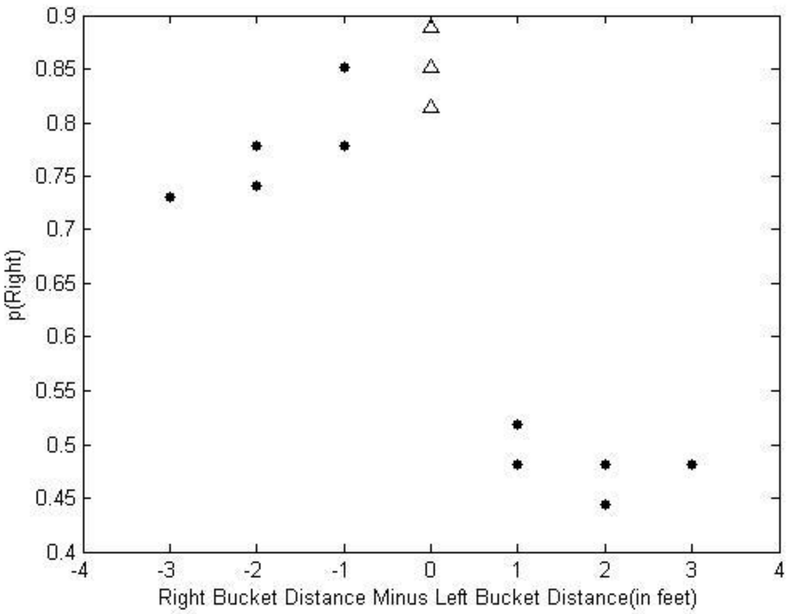

Figure 2-8. p(R) for all participants in Experiment 2.

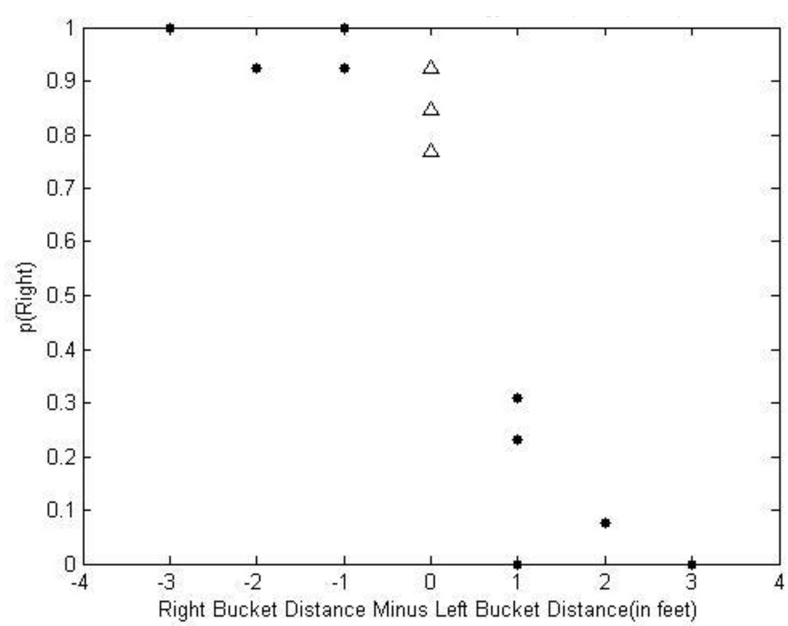

Figure 2-9. p(R) for the 13 close-bucket strategy participants in Experiment 2.

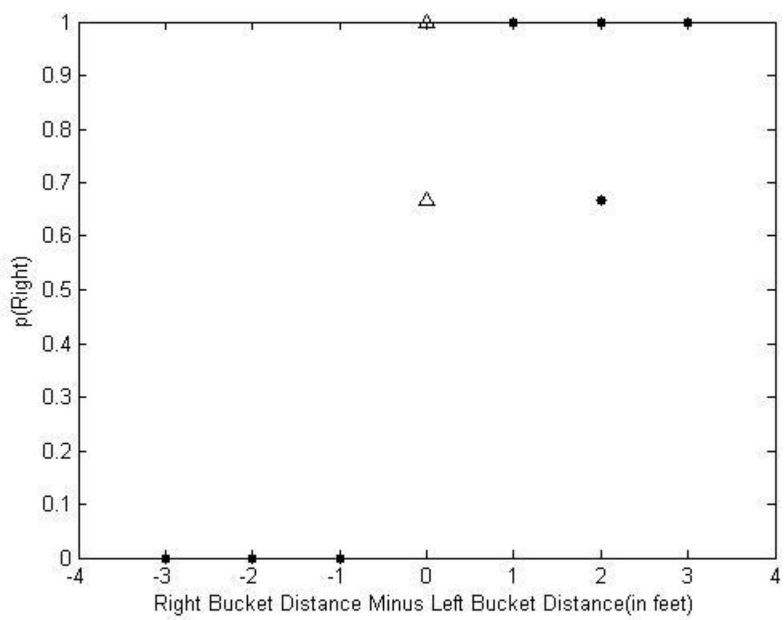

Figure 2-10. p(R) for the 3 far-bucket strategy participants in Experiment 2.

Figure 2-11 through Figure 2-13 show the probability, p(R), of lifting the right bucket under different right and left bucket distance differences (right distance minus left distance) in Experiment 3. The general patterns shown in Experiment 1 and Experiment 2 are also observed here.

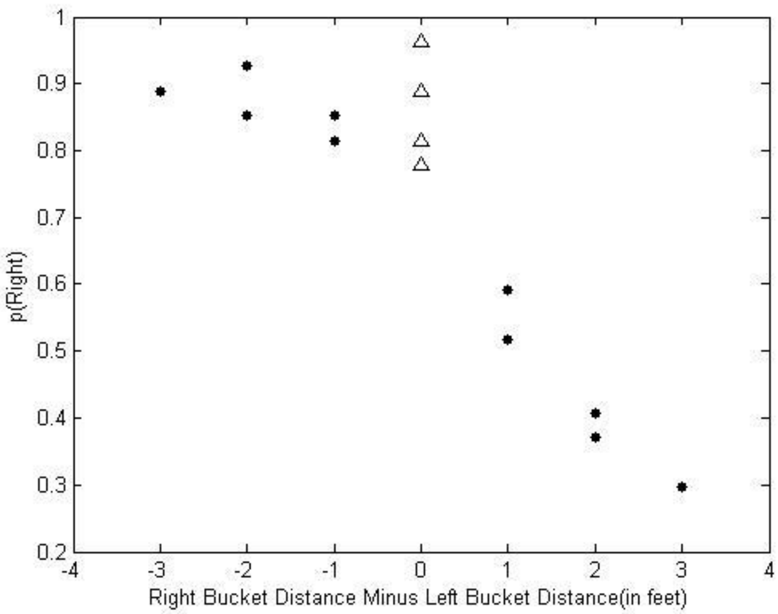

Figure 2-11. p(R) for all participants in Experiment 2.

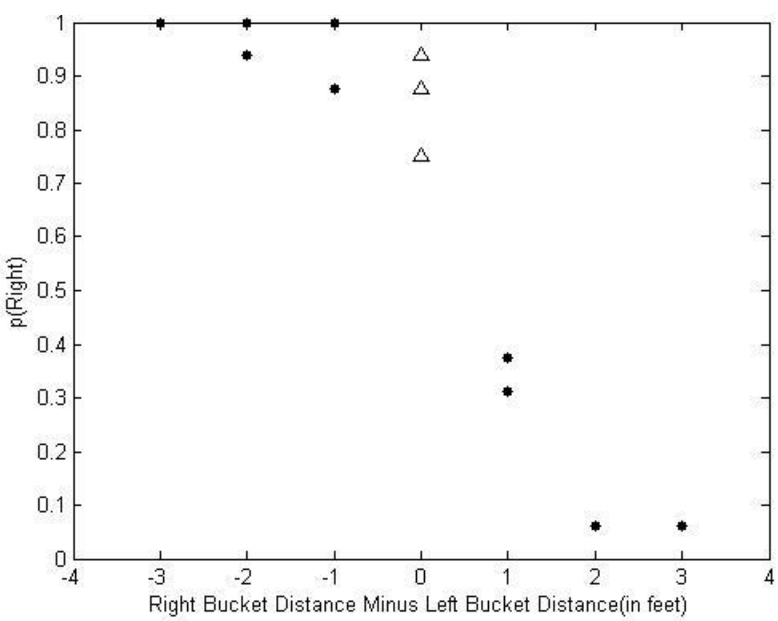

Figure 2-12. p(R) for the 16 close-bucket strategy participants in Experiment 3.

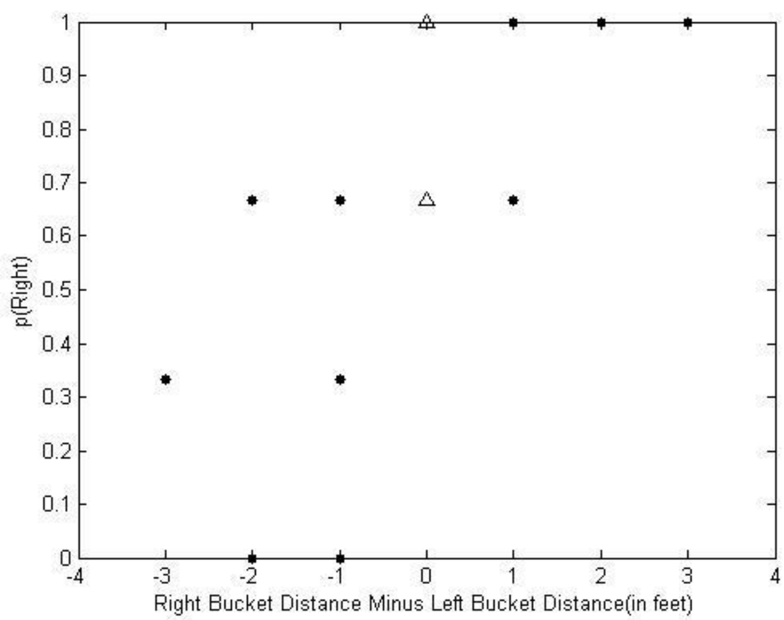

Figure 2-13. p(R) for the 3 far-bucket strategy participants in Experiment 3.

Height, Weight and Gender

I also asked if the participants adopted the close-bucket strategy differed from those who adopted the far-bucket strategy in terms of height, weight, or gender. I found that, in all three studies, height, weight and gender did not differ between these two strategy groups (all p>0.2). In addition, athletic experience was not a factor that differentiated these two groups (both groups had participants with or without athletic experience). Thus, the differences in strategy could not be attributed to these factors.

Discussion

The results of Experiment 1-3 suggest that there was a clear close bucket preference regardless of whether the bucket was unloaded or had a load of 3.5 lbs or 7 lbs weight. The number of trials in which participants chose a close bucket were significantly above chance level in all three studies. This close bucket (or "near object") effect is a new discovery.

The individual difference analyses showed that in all three studies, most participants adopted a consistent strategy in this task. There were only a couple of participants who did not. This result accords with the previous research indicating that people tend to stick to an action program within a task (Rosenbaum et al., 2010).

The fact that most participants preferred the close bucket rather than the far bucket in Experiment 1-3 is surprising because picking up a close bucket in this task entails doing more work, especially when the bucket was heavy (7 lbs). Participants who used this strategy (i.e., most participants) therefore behaved sub-optimally from the perspective of minimizing physical effort. Since doing more work than necessary is not a likely basis for action choices, it is reasonable to speculate that picking up the close bucket was based on some sort of cognitive heuristic.

CHAPTER 3

EXPERIMENT 4

Experiment 1-3 showed that participants significantly preferred the close bucket rather than the far bucket in the walking and reaching task. This was true regardless of the weight of the bucket. A hypothesis that might account for the close bucket effect is that, compared to picking up a far bucket, picking up a close bucket might allow participants to avoid the need to slow down their walking before reaching for the bucket. The assumption underlying this hypothesis is that, to walk from the start to the end of the aisle in the experiments reported above, participants had to increase their walking speed after starting and then had to decrease their walking speed before coming to a stop at the end. If participants had to slow down to pick up a bucket, it might have been costly to pick a bucket far from the start position in Experiments 1, 2, and 3 because those far positions were midway along the total walking path to the final resting place for the bucket, when walking speed was high. From this perspective, it might have been better to pick up a bucket because walking was still relatively slow.

To address this hypothesis in Experiment 4, I asked what would happen if the pick-up locations were "flipped," so they occupied the second (far) half of the walking aisle rather than the first (near) half of the walking aisle and thus were closer, on average, to the ending position than to the starting position. If participants preferred the close bucket in the previous experiments because they preferred picking up a bucket when their walking speeds were low, they would be expected to prefer the *far* bucket rather than the near bucket in Experiment 4.

Testing this prediction did not require the use of loaded as well as unloaded bucket, and so, only empty buckets were used. The reason why only empty buckets were needed is that the "slow-walk" hypothesis ascribes to the slowing of walking to aiming, as required to place one's hand under a bucket handle. As is well known from the literature on human motor control, movements slow down when precise aiming is required (Rosenbaum, 2010). This principle was supported in the walking-and-reaching research of Bertram and colleagues, summarized earlier (Bertram, Marteniuk, & Wymer, 1999; Bertram, Marteniuk, & Mackey 2000). If the near bucket preference found before were attributable to a weight-related feature of lifting, such as slowing down more to prepare to do a "power lift," one would not have expected the same near preference for unloaded buckets (Experiment 1) and for loaded buckets (Experiments 2 and 3). Therefore, it was logically unnecessary to use loaded as well as unloaded buckets in the "flipped distance" experiment, which is reported now.

Method

Twenty-seven Pennsylvania State University students participated for course credit. They ranged in age from 18 to 26 years. All the participants were right handed, assessed by the same Edinburgh handedness inventory, as in Experiments 1-3. This experiment was conducted under the approval of Penn State Institutional Review Board and informed written consent was obtained from each participant.

The apparatus was the same as in Experiment 1-3, except that I "flipped" the four possible locations of the bucket-bearing platforms from 2, 4, 6, or 8 feet from the starting position to 2, 4, 6, or 8 feet from the ending position (i.e. 8, 10, 12, or 14 feet from the start line). All four locations were therefore located within the far half of the walking path, whereas in Experiment 1-3 the distances were in the near half of the walking path. The buckets were empty in this flipped distance study, so this experiment was, specifically, the flipped version of Experiment 1. The diagram of the setup is shown in Figure 3-1.

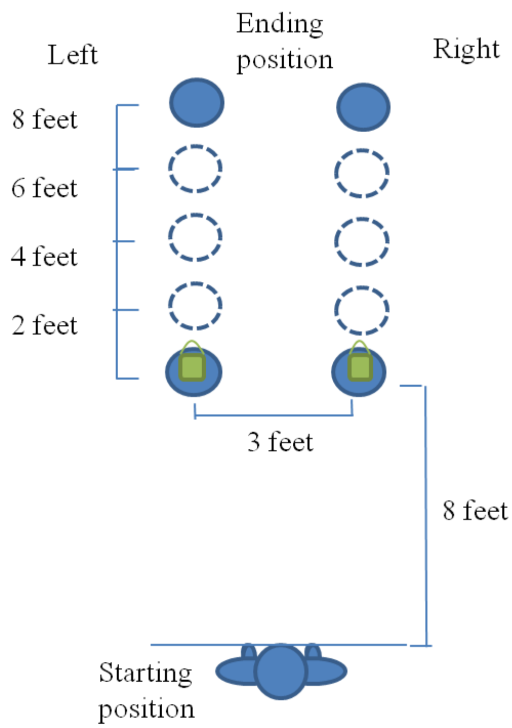

Figure 3-1. A representative condition of Experiment 4.

Results

The numbers of trials in which participants picked up a far bucket or a close bucket out the 12 trials with unequal distances are plotted in Figure 3-2. A one sample t-test suggested that the number of trials in which participants picked up the close bucket was not significantly different from 6, or 50% of the total 12 different-distance trials (t=0.34, p=0.737). Thus, there was no close bucket preference in this study.

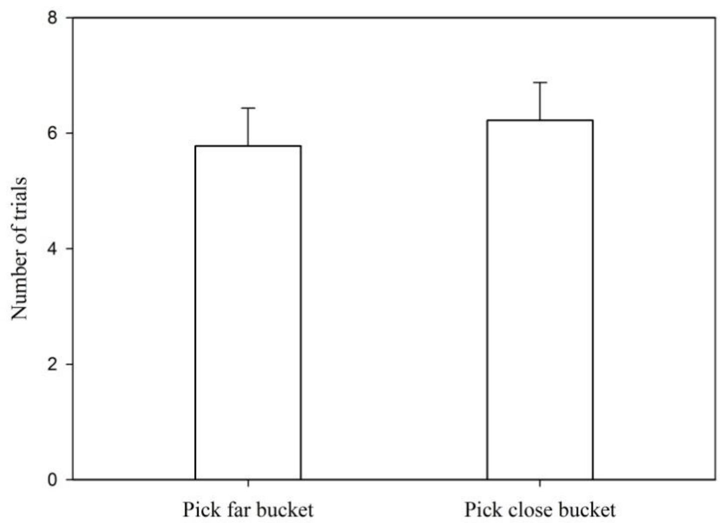

Figure 3-2. Mean number of trials in which participants picked up a close bucket or a far bucket in the 12 trials with different distances in Experiment 4. The error bars represent +1 standard error.

The bar graph in Figure 3-3 shows the average number of trials in which participants chose a right bucket or left bucket in the total of 16 trials. To test if there was a right hand bias in this flipped distance study, I did a one sample t-test to compare the average number of trials in which participants chose the right bucket with 8, half of the total of 16 trials. The right hand bias was significant, $t = 11.69$, $p < .001$. As in the previous experiments, nearly all participants chose the right bucket in the 4 equal distance trials. The average proportion of participants choosing right bucket in these 4 trials was 0.97. The right hand preference was somewhat lower in the 12 unequal position trials, where the average proportion of participants choosing the right bucket was 0.72. This outcome implies that the impact of the distances amounted to 25% (97% - 72%).

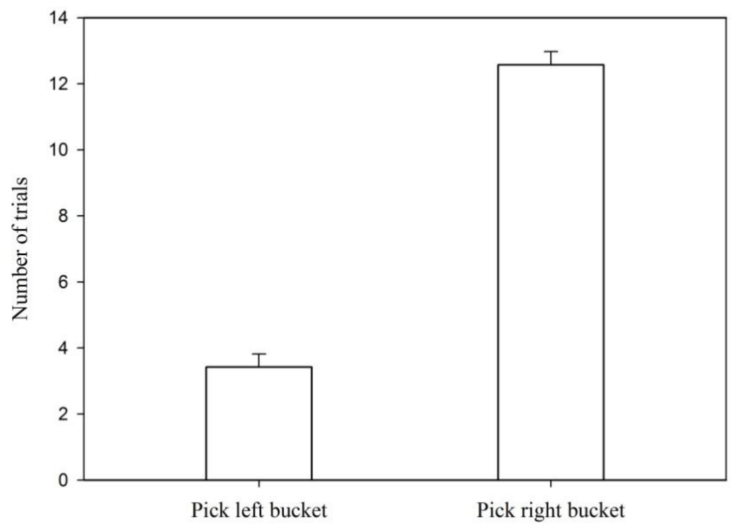

Figure 3-3. Mean number of trials in which participants picked up a right bucket or a close bucket in Experiment 4. The error bars represent +1 standard error.

Strategies

Following the same procedure of assigning individuals to groups in Experiment 1-3, I did the same thing for the participants of Experiment 4, comparing their groupings to those of Experiment 1, where the buckets were also unloaded. The assignments are shown in Table 3-1.

A Chi-square test showed that the left two columns (the number of participants in the close bucket strategy and the far bucket strategy category) were significantly different in the two experiments, Chi-square = 4.52, df = 1, p = 0.033. This result indicates that the proportion of participants using the close bucket strategy and far bucket strategy changed from Experiment 1 to Experiment 4.

Table 3-1. Number of participants out of 27 per experiment who adopted the close-bucket, far-bucket, right-hand, left-hand or no consistent strategy in the 12 different-distance trials in Experiments 1 and 4.

	Number of participants				
Experiment	Close bucket strategy	Far bucket strategy	Right hand strategy	Left hand strategy	No consistent strategy
1	17	3	4	1	2
4	9	8	8	0	2

Figure 3-4 through Figure 3-6 show the probabilities of picking up a right bucket, either for all participants (Figure 3-4), for participants in the close-bucket strategy group (Figure 3-5), and for participants in the far-bucket strategy group (Figure 3-6). In the graph of all participants, the dots look messy and do not show a clear linear trend, indicating that generally there was not a single close or far bucket strategy rule to depict the relation between P(R) and the distance difference of right and left bucket. However, when plotting the data of the close-bucket strategy group and the far-bucket strategy group separately, it is clear that close-bucket strategy participants and far-bucket strategy participants showed the opposite pattern between p(R) and distance differences. A strong close bucket preference was shown in the close-bucket strategy group and a strong far bucket preference was shown for the far-bucket strategy group. These graphs indicate that individual differences played an important role in this experiment.

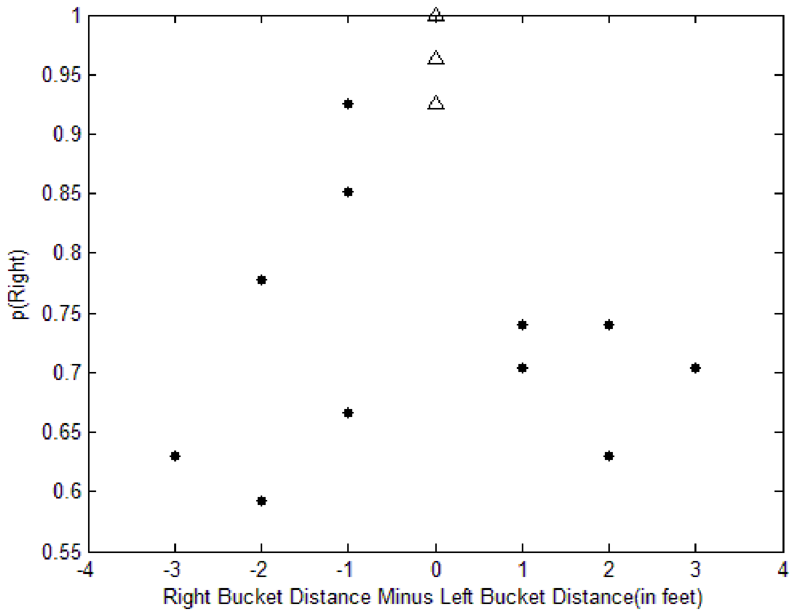

Figure 3-4. Probability, p(R), of lifting the right bucket as a function of the difference between right bucket distance and the left bucket distance in Experiment 4. p(R) is averaged over all 27 participants. In the graph, the dots on the left correspond to the conditions in which the right bucket was closer, and the dots on the right correspond to the conditions in which the left bucket was closer. The triangles represent the conditions in which the left and right buckets were equally far from the start (or final) position.

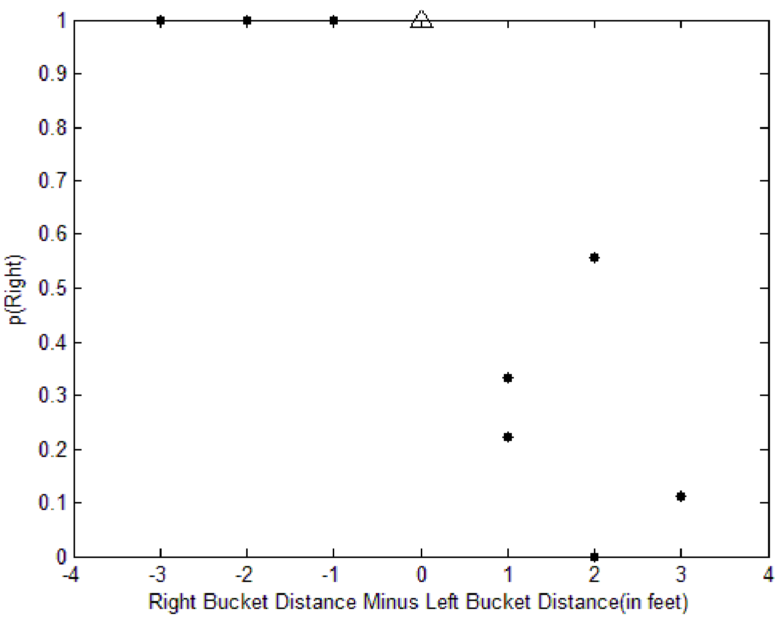

Figure 3-5. Probability, p(R), of lifting the right bucket as a function of the difference between right bucket distance and the left bucket distance in Experiment 4 for the 9 participants who used the close-bucket strategy.

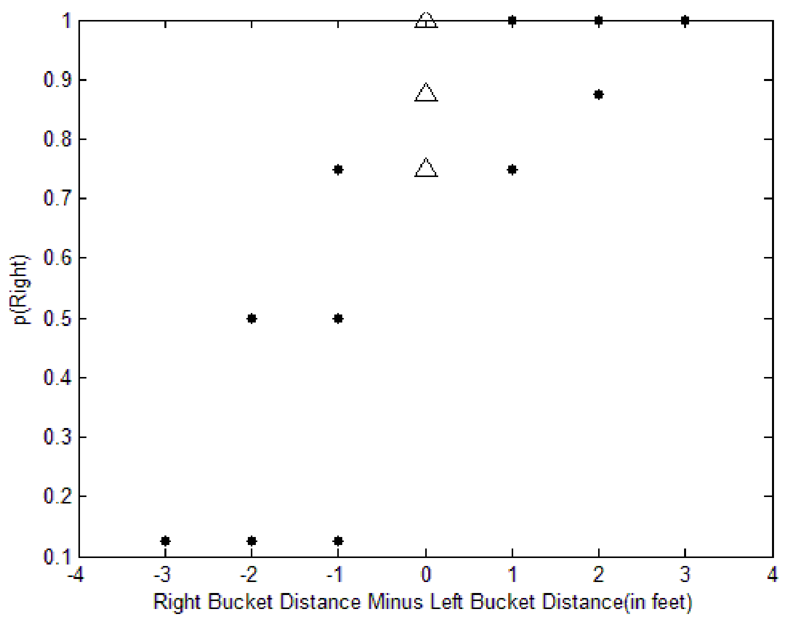

Figure 3-6. Probability, p(R), of lifting the right bucket as a function of the difference between right bucket distance and the left bucket distance in Experiment 4 for the 8 participants who used the far-bucket strategy.

To find out if the close bucket strategy participants was different from the far bucket strategy participants in terms of height, weight and gender, I performed all relevant two-sample t tests. I found no significant differences in terms of height, weight, or gender between the two groups (all $p>0.8$).

Discussion

The results of Experiment 4 suggest that, when the left and right pick-up location were near the ending position, not near the starting position as in Experiments 1-3, the close bucket effect was eliminated. This was both demonstrated by a reduced number of trials in picking up the close bucket and a reduced number of participants who consistently used the close bucket strategy. There was no close bucket preference in Experiment 4, whereas there was a pronounced close-bucket preference in Experiments 1-3. Meanwhile, there was no obvious far bucket preference either in Experiment 4. The number of trials in which participants chose the far bucket was similar to the number of trials in which participants chose the close bucket. Also, there were nearly equal numbers of participants who adopted the close bucket strategy or the far bucket strategy.

These results suggest that the “slow walk” hypothesis might be true to some degree. Participants who preferred the far bucket in Experiment 4 picked up the bucket while approaching the end position might have done so because their walking speed decreased as they approached the stop position. However, the “slow walk” hypothesis alone is not sufficient to explain why there were still as many participants who preferred the close bucket as the far bucket in this experiment. The “slow walk” hypothesis predicted that participants would prefer the far bucket to the close bucket, which is not what was observed. Therefore, some other factor must have biased participants toward the close bucket, and it is very likely that it was some cognitive factor. (Height, weight, and gender did not account for the differences in strategies.)

CHAPTER 4

EXPERIMENT 5

In Experiment 1-3, I found that the participants preferred the shorter pre-lift distance when the pre-lift distances differed, or they preferred the right bucket when the pre-lift distances were the same. However, in those three experiments and also in Experiment 4, the pre-lift distances co-varied with the post-lift distances. This was true because the far tables had the same distances from the start place all the time. Thus, the results could be explained by saying that participants preferred to maximize their post-lift distance, not that they preferred to minimize their pre-lift distances. It is at least conceivable that this was the case if maximizing the post-lift distance allowed participants to achieve greater control after picking up the bucket and carrying it to the set-down site.

In Experiment 5, I disassociated pre-lift distance and post-lift distance by varying them independently. If minimizing pre-lift distance was the reason for picking up the close bucket, then the participants in Experiment 5 should still prefer the closer bucket, regardless of the post-lift distance. Otherwise, if maximizing post-lift distance was the real reason for picking up the close bucket, then the participants in Experiment 5 should obey that constraint, not necessarily minimizing pre-lift distance in a consistent fashion.

Method

Twenty-seven Pennsylvania State University students participated for course credit. The participants' age ranged from 18 to 26 years. All participants were right handed, assessed by the same Edinburgh handedness inventory. This experiment was conducted under the approval of

Penn State Institutional Review Board and informed written consent was obtained from all participants.

The apparatus was the same as in Experiment 1-4, except that in Experiment 5, the 16 experimental trials used short (2 feet) or long (8 feet) pre-lift distances and short (2 feet) or long (8 feet) post-lift distances. Table 4-1 lists all the combinations of pre-lift distances and post-lift distances for the left and right sides. To help visualize these conditions, Figure 4-1 shows an example diagram depicting the setup of one trial, denoted L28R88. The buckets were unloaded in this experiment.

Table 4-1. Design of Experiment 5*

Left side				**Right side**			
		Post-lift				Post-lift	
		short	long			short	long
Pre-lift	short	L22	L28	**Pre-lift**	short	R22	R28
	long	L82	L88		long	R82	R88

*For example, L28 means that for the left side choice, the pre-lift distance is 2 feet and the post-lift distance is 8 feet. R22 means that for the right side choice, the pre-lift distance is 2 feet and the post-lift distance is 2 feet.

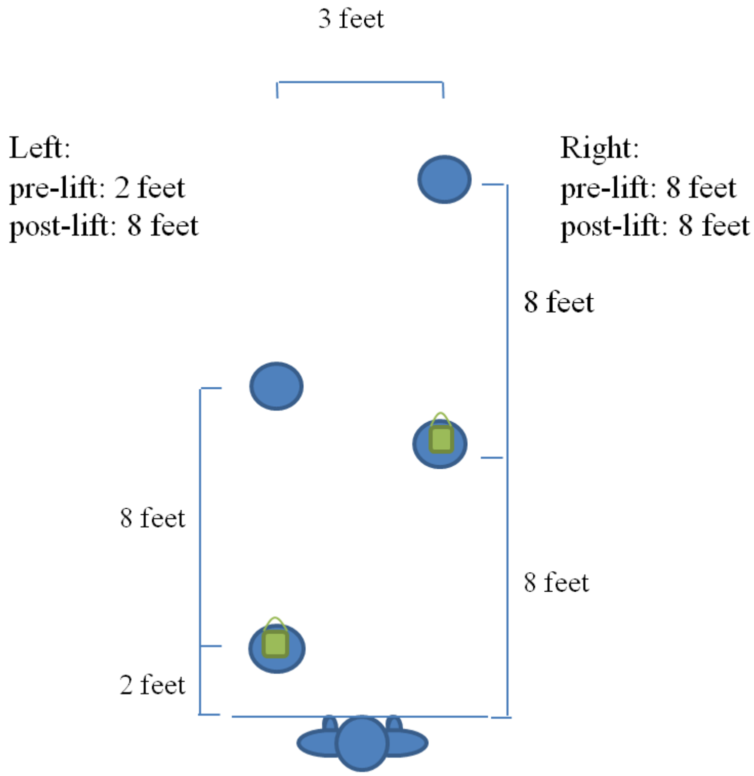

Figure 4-1. Diagram of one of the trials, L28R88, in Experiment 5. For the left side choice the pre-lift distance is 2 feet, and the post-lift distance is 8 feet. For the right side choice, the pre-lift distance is 8 feet, and the post-lift distance is also 8 feet.

Results and Discussion

The results of Experiment 5 are plotted in Figure 4-2, where it can be seen that participants did not try to maximize post-lift distance. If anything, they tried to minimize post-lift distance.

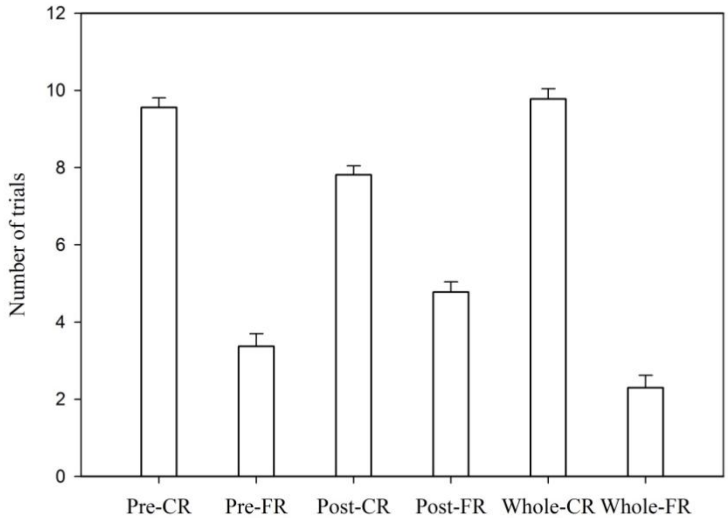

Figure 4-2. Mean number of trials in which participants picked up the bucket based on the following strategies: Pre-lift close or right hand otherwise (Pre-CR); Pre-list far or right hand otherwise (Pre-FR); Post-lift close or right hand otherwise (Post-CR); Post-list far or right hand otherwise (Post-FR); Pre- and post-lift close or right hand otherwise (Whole-CR); Pre- and post-lift far or right hand otherwise (Whole-FR). Error bars are +1 standard error of the mean for the 27 participants in Experiment 5.

More participants followed the Pre-CR rule than the Pre-FR rule (paired t-test, $t= 12.95$, $p=0.000$). Likewise, more participants followed the Post-CR rule than the Post-FR rule ($t= 7.26$, $p=0.000$). In all, participants preferred a choice with less total distance. Maximizing post-lift distance was not a priority.

CHAPTER 5

GENERAL DISCUSSION

I have reported five experiments to explore decision-making in a walking and reaching task. In this series of experiments, I discovered a new phenomenon: People generally prefer to pick up a close bucket at the cost of transporting it a longer distance, at least when the range of bucket positions is close rather than far. In Experiment 1-3, I demonstrated that participants preferred to choose to pick up a close bucket when the distance from the start line to the picking up positions of the left and right choices were unequal and when the buckets were in the near half of the whole walking path, even if the bucket was as heavy as 7 pounds. In Experiment 4, I flipped the four possible picking up positions to the far half of the walking path, and I found that the close bucket preference was reduced to the point that the probability of choosing the far bucket was the same as the probability of choosing the near bucket. In Experiment 5, by independently varying the pre-lift distance and the post-lift distance, which were coupled in Experiments 1-4, I showed that participants did not prefer a longer post-lift distance, thereby confirming that the close bucket effect discovered in Experiment 1-3 was indeed attributable to the aim of minimizing pre-lift distance rather than maximizing post-lift distance. Minimizing lifting (or carrying) distance was, in general, a preference in the final experiment.

The close bucket effect that has been revealed in this study is strong, since weight did not modulate this effect. Moreover, from Experiment 5, one can be assured that the close bucket effect reflected participants' preference for minimizing the pre-lift distance. From the perspective of physical effort, picking up a close bucket and transporting it a longer distance is not an optimal choice, especially when the bucket is as heavy as 7 lbs. Given this finding, the present study provides strong evidence that motor control is not only governed by biomechanical optimization, at least as measured here.

What is the source of the close bucket effect? What heuristic gave rise to this strategy? I have several hypotheses. The first two include biomechanical factors, which must not be ruled out a priori, though, as it turns out, I will show that both of them fail. The other four hypotheses are cognitive. None of these hypotheses fail. They will be considered after the biomechanical hypotheses are reviewed=.

One biomechanical hypothesis is the *Slow walk* hypothesis. This hypothesis was discussed and tested in Experiment 4. The idea was that participants would avoid picking up a bucket at a fast walking speed, and since the walking profile tends to be a bell-shaped function (speed up from rest then slow down approaching the next rest), they might have preferred a bucket close either to the starting position (in Experiments 1, 2, or 3) or close to the ending position in Experiment 4). The results of Experiment 4 suggested that this hypothesis was insufficient to account for the close bucket effect because even if the buckets were all closer to the ending position rather than to the starting position, many participants still preferred the close bucket.

The other biomechanical hypothesis is one that has not yet been introduced. I call it the *Ipsilateral support* hypothesis. The idea is that participants might have preferred the close bucket to make it easier for them to walk in such a way that they could arrive at the pick-up point with the foot ipsilateral to the lifting hand. Walking over a shorter distance might have made this foot placement easier than walking over a longer distance. The rationale for the hypothesis is that during normal walking, the arm swinging forward on one side of the body pairs with the foot stepping forward on the other side of body. Thus, during walking, people show contralateral upper arm swinging and foot stepping, but, as found in previous research, the in-phase relation of contralateral limbs during normal gait switches into an in-phase relation of ipsilateral limbs at the time when walking is coordinated with reaching (Cockell, Carnahan, and McFadyen ,1995), as reviewed earlier in this thesis. Thus, accommodating the foot steps to achieve an ipsilateral support might apply to our study. Participants might need to plan their steps so they can use their ipsilateral leg to support the lifting. In that case, it is possible that a shorter pre-lift distance would make it easier to plan for the ipsilateral lift.

To test this hypothesis, I initiated an analysis of the videos of the walking and reaching in Experiment 1 (0 lbs bucket) and in Experiment 3 (7 lbs bucket), frame by frame. The question was which leg was the supporting leg when the participant's hand touched the bucket handle for lifting. The support leg was defined as the leg in front and flat on the ground. I had two research assistants code the video of Experiment 1, independently. Likewise, the video of Experiment 3 were coded by another two research assistants independently. For each experiment, both research assistants coded all trials of all participants. There were 27×16= 432 trials in all.

The result of the analysis was that in both Experiment 1 and in Experiment 3, the proportion of trials in which participants used the ipsilateral leg to support the lifting was at about chance level (Experiment 1: RA 1 coding: 46.7%, RA 2 coding: 50%; Experiment 3: RA 1 coding: 45.6%, RA 2 coding: 49.1%). Confidence could be placed in these values in the sense that the agreement between the two coders for each experiment was high. The Pearson product-moment correlation coefficient of the 0 (not ipsilateral support) and 1 (ipsilateral support) coding over all trials between the two coders for Experiment 1 was 0.78, and for Experiment 3 was .66. Both correlations were highly significant (p-values < 0.001). Thus, participants did not adopt an ipsilateral foot support at the time of reaching the bucket. I am not sure why participants did not show ipsilateral lifting in this study whereas such ipsilateral support has been shown in previous studies of walking and reaching (Carnahan et al., 1996), but one possibility might be that the previous studies did not require path choices. Instead, participants were told to do a single walk-and-reach task. Here, by contrast, choices were required. Another possibility is that lifting a bucket is different from lifting the objects used in those earlier studies. In any case, it seems that the *Ipsilateral support* hypothesis fails to account for the close bucket effect in the present study. This means that the ipsilateral support hypothesis, like the other biomechanical hypothesis -- the *slow walk* hypothesis -- could not explain why the close bucket strategy was used.

Having ruled out, or not found evidence for, the two biomechanical hypotheses, I turn next to the more cognitive hypotheses. These were broached in the Introduction and are reviewed again here.

One cognitive account is the *attention* hypothesis. According to this hypothesis, a close object attracts more attention than a far object, leading participants to pick up the close bucket. The attention hypothesis is consistent with the idea that objects (both target and non-target) in the environment can attract action-based attention. Evidence that action is modulated by attention has been found in small-scale reaching and grasping studies, in studies where participants reach and grasp without walking through the environment (e.g. Tipper, Howard, & Jackson, 1997; Welsh & Elliott, 2004). In the current study, the close bucket effect shown in Experiments 1-3 might reflect attention, as could the close bucket strategy manifested by half the participants in Experiment 4. In fact, it is conceivable that only half the participants in Experiment 4 showed the close bucket strategy exactly because of attention: The farther away two objects are, the less strongly the closer object would be expected to attract attention compared to the farther object.

Another possible cognitive account is the *uncertainty* hypothesis. It postulates that there is less uncertainty in planning for the pick-up of a close bucket than a far bucket. Picking up an object during walking requires precise spatial and temporal coordination of the whole body. A shorter pre-lift distance would make it easier to plan the steps towards the object, irrespective of whether the ipsilateral foot is placed on the ground, which may not be a critical requirement, judging from the analysis reported a few paragraphs back.

The c*ognitive load* hypothesis is another possible cognitive account. This hypothesis is inspired by communicating with participants after the experiment, many of whom said they preferred the close bucket because they "just wanted to get it done." By completing the pick-up earlier, the (small) cognitive load of this aspect of the task could be relieved. Such a possibility is familiar in psychology. As first found by the Russian psychologist, Zeigarnik, incomplete tasks are remembered better than completed tasks. This is known as the Zeigarnik effect. For a review, see Van Bergen (1968). The Zeigranik effect has been replicated many times. Relatedly, it has been found that cognitive effort is required to hold task goals in working memory and that people are motivated to complete tasks sooner rather than later if they can (Kane & Engle, 2003; Schiffman & Greist-Bousquet, 1992).

There is also, finally, a *personality trait* hypothesis. This hypothesis comes from the observation that there were individual differences in using the close bucket or far bucket strategy in each experiment, but I could not attribute these to differences in variables such as participants' height, weight, or gender. Thus, individual differences lying in some more cognitive or psychological factor might account for the strategy differences that were observed here.

In the future, more studies could be done to test the hypotheses adduced here. To test the *attention* hypothesis, some feature (e.g. color) of the far bucket could be changed to make it more prominent. To test the *uncertainty* hypothesis, steps could be marked on the floor. To test the *cognitive load* hypothesis, a dual task experiment could be conducted in which participants try to maintain a list in working memory to see if, in a situation like that used in Experiment 4, where participants preferred the far bucket at a higher rate than before, that preference could be attenuated when working memory is occupied as compared to when it is not. Last but not least, it would be worth testing the *personality trait* hypothesis by administering personality tests to participants to see whether some aspect of personality, such as impulsivity, predicts the close bucket preference. Joining personality research with motor-control research would be an exciting new venture stimulated by the discovery made here.

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APPENDIX A

INSTRUCTIONS FOR EXPERIMENT 1

1) This study is about walking and reaching.

2）As you can see, there is a blue line on the floor with a grey line in the middle. Please now face the tables and stand with your left foot on the left side of the grey line and your right foot on the right side of the grey line. Also please align the tips of your toes just behind the blue line. At the start of each trial, you will be asked to stand in this position.

3) Notice that there are four identical tables in front of you, two on your left side and two on your right side. Two of them are close to you and the other two are far from you. For each close table there is a bucket placed on the center of the table top. The locations of the left and right table near you will change across trials, but the far tables will be kept at the same spot.

4) During the experiment you will have two choices for each trial. One choice is to walk and grasp the bucket on the left and carry it to the left far table. The other choice is to walk and grasp the bucket on the right and carry it to the right far table. Please note that if you choose to walk and grasp the left bucket, you must use your left hand to grasp the handle of it. Likewise, if you choose to walk and grasp the right bucket, you must use your right hand to grasp the handle of it. Please walk in-between the two tables and reach for the bucket in a natural way without stopping.

5) In each trial, you should choose only one of the two choices to perform. Please note that you should choose the option that is easier for you. There is no right or wrong solution. What we are interested in is which task you think is easier to perform in each trial.

6) Each trial will end after you place the bucket on the far table. Please leave it there and walk back to the starting position. Before the next trial, you will be asked to face away from the tables and stand behind the blue line. While you are waiting, we will set up the tables for the next trial. Then I will ask you to turn around.

7) After you turn around please put your feet on either side of the grey line with your toes touching the blue line. Then please take a brief moment to consider the options in front of you. After you make sure that your feet are in the right place and decide the option, you can start to perform the task which you think is easier. You don't have to think hard about your choice. I will remind you about this procedure. There is no time limit and again please walk and reach in a natural way without stopping.

8) To help us study walking and reaching we will be videotaping you in each trial. To help us analyze the video, we will ask you to place four markers on your sleeve and shoes. I will show you where to put them. They have a light adhesive and will not damage your clothes.

9) If you are not comfortable with wearing the markers or being videotaped please let me know now. The videos will not be shown outside of this lab unless you give us permission for them to be shown after the experiment is over.

10) We now ask that you please turn your cell phone or any other electronic devices off during the study. I'd like you to tell me in your own words what you will be doing to make sure that I explained everything clear.

11) Do you have any questions?

APPENDIX B

HUMAN SUBJECT APPROVAL

Date: September 14, 2011

From: Jodi L. Mathieu, Research Compliance Coordinator

To: David A. Rosenbaum

Subject: Results of Review of Continuing Progress Report - Expedited **(IRB #34999)**

Approval Expiration Date: September 13, 2012

"Control of Movement Sequences"

The Continuing Progress Report for your project was reviewed and approved by the Institutional Review Board (IRB). By accepting this decision, you agree to obtain prior approval from the IRB for any changes to your study. Unanticipated participant events that are encountered during the conduct of this research must be reported in a timely fashion.

Attached is/are the dated, IRB-approved informed consent(s) to be used when enrolling participants for this research. Participants must receive a **copy** of the approved informed consent form to keep for their records.

If signed consent is obtained, the principal investigator is expected to maintain the original

signed consent forms along with the IRB research records for at least three (3) years after termination of IRB approval. For projects that involve protected health information (PHI) and are regulated by HIPAA, records are to be maintained for six (6) years. The principal investigator must determine and adhere to additional requirements established by the FDA and any outside sponsors.

If your study will extend beyond the above noted approval expiration date, the principal investigator must submit a completed Continuing Progress Report to the Office for Research Protections (ORP) to request renewed approval for this research.

On behalf of the committee and the University, thank you for your efforts to conduct research in compliance with the federal regulations that have been established for the protection of human participants.

Please Note: The ORP encourages you to subscribe to the ORP listserv for protocol and research-related information. Send a blank email to: L-ORP-Research-L-subscribe-request@lists.psu.edu

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Attachment