Published in final edited form as:

Exp Brain Res. 2017 June ; 235(6): 1793–1807. doi:10.1007/s00221-017-4879-6.

Motor Decisions Are Not Black and White: Selecting Actions in the “Gray Zone”

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Abstract

In many situations, multiple actions are possible to achieve a goal. How do people select a particular action among equally possible alternatives? In six experiments, we determined whether action selection is consistent and biased toward one decision by observing participants' decisions to go over or under a horizontal bar set at varying heights. We assessed the height at which participants transitioned from going over to under the bar within a “gray zone”—the range of bar heights at which going over and under were both possible. In Experiment 1, participants' transition points were consistently located near the upper boundary of the gray zone, indicating a bias to go over rather than under the bar. Moreover, transitional behaviors were clustered tightly into a small region, indicating that decisions were highly consistent. Subsequent experiments examined potential influences on action selection. In Experiment 2, participants wore ankle weights to increase the cost of going over the bar. In Experiment 3, they were tested on a padded surface that made crawling under the bar more comfortable. In Experiment 4, we introduced a secondary task that required participants to crawl immediately after navigating the bar. None of these manipulations altered participants' decisions relative to Experiment 1. In Experiment 5, participants started in a crawling position, which led to significantly lower transition points. In Experiment 6, we tested 5- to 6-year-old children as in Experiment 1 to determine the effects of social pressure on action selection. Children displayed lower transition points, larger transition regions, and reduced ability to go over the bar compared to adults. Across experiments, results indicate that adults have a strong and robust bias for upright locomotion.

Keywords

Action selection; motor decisions; affordance perception; locomotion; obstacles

People can perform a variety of actions. Even within an action category such as locomotion, the possibilities are manifold. We can walk, run, leap, skip, crawl, limbo, and cartwheel. And even within a particular type of locomotion, the possibilities are countless. Walkers can adjust their gait by turning, ducking, changing their step length, and varying walking speed. For any given situation, how do people select which action to do? All things being equal, presumably people continue their current action: Walkers keep walking at the same pace and manner. But an obstacle presents an impetus to modify the current action or to select a

different action. A barrier in the path, for example, can instigate a variety of strategies for going over (increase height of stepping leg, rise on tiptoes, hurdle the obstacle) or under the barrier (duck head, squat, scoot, crawl).

Affordances for Action

Possibilities for action depend on the fit between features of the environment and characteristics of the body—what Gibson (1979) termed “affordances.” For example, adults step over low barriers and duck under high barriers (Franchak, Celano, & Adolph, 2012; Pufall & Dunbar, 1992; Stefanucci & Geuss, 2010). Changes in the environment alter affordance relations: As barrier height increases, going over becomes impossible, and as barrier height decreases, going under becomes impossible. Similarly, changes in the body alter the affordances for walking: High-heeled shoes or heavy hiking boots make it harder to step over a barrier, and bulky clothing or dramatic weight gain make it harder to squeeze under. Affordance relations exist regardless of whether they are perceived or used (Franchak & Adolph, 2014).

Although perceiving affordances is ubiquitous in everyday guidance of motor decisions, previous work has focused primarily on detection of particular affordances, not on using information about various affordances to select an appropriate action. For example, in previous studies, participants judged whether they could walk through doorways of different widths without rotating their shoulders, squeeze through tight doorways without becoming wedged, walk under barriers without ducking their heads, or step onto various riser heights without using their hands (Franchak et al., 2012; Stefanucci & Geuss, 2010; van der Meer, 1997; Warren, 1984; Warren & Whang, 1987). Although affordance judgments were impressively accurate, participants were not asked to select actions from among an array of alternatives. Rather, the choice was a binary yes or no decision about a particular affordance.

However, in many situations, action selection is not simply a binary, “black or white,” decision. The decision space is more like a “gray zone” because a variety of actions are available to achieve a goal. Moreover, different actions can be nested within the larger plan (e.g., walking to a shelf to pick up a book; sequencing a series of walking steps to navigate a flight of stairs; grasping a hammer to pound a peg). People must select one of several possible actions and perceive the nested affordances within their selected action (Mark, Ye, & Smart, 2017; Stoffregen, 2003; Wagman, Caputo, & Stoffregen, 2016; Comalli, et al., 2016).

Selecting Which Action to Do

On what basis do people select an action from an array of viable alternatives, and how consistent are their choices? To answer these questions, participants must be tested in a situation where more than one action is possible. For example, given the options of walking straight through or around an aperture to a goal, adults walk straight through when the aperture is at least 1.4 times their shoulder width and detour around the obstacle when the aperture is smaller than 1.4 times their shoulder width (Hackney, Vallis, & Cinelli, 2013). But why?

When multiple affordances are possible, people may weigh the costs and benefits of each possibility (Kording & Wolpert, 2006; Trommershäuser, Maloney, & Landy, 2008). If the *perceived* costs and benefits are not equal, people should consistently select the action that minimizes costs and maximizes benefits. However, if the perceived costs and benefits of two options are approximately equal, people should select the two actions with equal frequency. Consider, for example, using your dominant or non-dominant hand to pick up a rod. Either hand would do (the gray zone covers most of the reaching space), but grasping with the dominant hand is more habitual, efficient, and comfortable. Accordingly, adults always use their dominant hand if the rod is at midline or toward the dominant side; they always use their non-dominant hand if the rod is far toward the non-dominant side; but they use their two hands equally when the rod is within a region located slightly past midline toward the non-dominant side (Bryden, Mayer, & Roy, 2011). The size of this “transition region,” where people use multiple strategies (here, the narrow region of locations slightly closer to the non-dominant hand), reflects the consistency of action selection. A larger transition region indicates less consistent action selection and a smaller region indicates more consistent action selection. The “transition point,” the increment at which responses change from one action to another, reflects whether action selection is biased. In this case, the location of the transition point indicates a bias toward using the dominant hand.

Energetic cost and comfort can influence action selection. Young adults grasp distant objects without leaning if the object is well within their arm span. But at farther, still graspable distances, participants lean forward, despite the possibility of grasping without leaning (Mark, et al., 1997). Presumably, adults unnecessarily lean forward because leaning is more comfortable than fully extending the arm with a straight back. Changes in body mass or dynamic capabilities (e.g., carrying a load) affect energetic cost (Browning, Modica, Kram, & Goswami, 2007), and in turn may affect which action people select (whether to step over or go under a barrier). All else being equal, an action that is easier to perform or more comfortable is preferable to a difficult or uncomfortable one.

The demands of future actions can influence current action selection. Adults consistently choose unconventional or awkward starting positions that allow for a comfortable ending position for a future action—the so-called “end-state comfort” effect (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Rosenbaum et al., 1990). Adults plan their next locomotor action by taking an initially awkward step when crossing stepping-stones to ensure that they can easily avoid an obstacle on a subsequent step (Cowie, Smith, & Braddick, 2010). They plan for a comfortable final grasp position by using an underhand grasp to grip the handle of a hammer when the hammerhead points toward their dominant hand so that they can pound a peg using an overhand radial grasp (Comalli, et al., 2016).

Minimizing changes to one’s current posture can also influence action selection. Adults walk around an aperture rather than through it if they need to turn their shoulders to pass through (Hackney et al., 2013). Furthermore, motor decisions can be influenced by a non-physical cost. For example, avoiding the embarrassment of deviating from social norms may dissuade people from selecting certain actions (e.g. running in public despite being late for a meeting).

Current Studies

In six experiments, we investigated factors that govern action selection from among viable alternatives by testing people's decisions to go over or under a horizontal bar set at varying heights. For all experiments, a "gray zone" spanned the heights where navigating over and under the bar were *both* possible. In each experiment, we estimated an individualized gray zone for each participant based on his or her actual ability to go over and under various bar heights. We estimated a "transition region," based on the span of bar heights in which participants sometimes went over and sometimes went under the bar, and a "transition point" midway between the highest bar height they always went over and the lowest bar height they always went under. Based on these two estimates, we assessed the consistency of action selection (the size of the transition region) and where the perceived cost/benefit ratio changed from favoring one action to another (the location of the transition point).

Experiment 1 determined the pattern of adults' decisions and served as the control for subsequent experiments. In Experiments 2–6 we manipulated potential factors affecting transition regions and transition points in the gray zone by attempting to alter the cost/benefit ratios of going over or under the bar. In Experiment 2, we increased the cost (energetics) of going over the bar by putting ankle weights on participants. In Experiment 3, we reduced the cost (discomfort) of crawling under the bar by testing participants on a padded surface. In Experiment 4, we increased the cost of maintaining an upright posture to go over the bar by requiring participants to get on their hands and knees immediately after passing through the opening. In Experiment 5, we reduced the cost of modifying posture to go under the bar by starting participants in a crawling position. Finally, in Experiment 6 we tested a sample of 5- to 6-year-olds—an age where social pressures to remain upright are presumably reduced and behavior is generally more variable than in adults. Each participant was observed in only one experiment, so comparisons between experiments were between subjects.

Experiment 1: Going Over or Under a Barrier (Control)

In Experiment 1, participants navigated over or under a horizontal bar that was raised and lowered to varying heights. The decision to go over or under allowed a variety of actions and participants could select freely among them. We determined each participant's gray zone (the region in which both going over and under were possible) and examined the distribution of decisions in the gray zone.

Method

Participants—We recruited 20 healthy, young adults (12 women, 8 men) between 19 and 29 years of age ($M = 22.0$) through the psychology department subject pool and word of mouth; participants received course credit or \$10 as compensation. They wore stretchy sports pants and fitted shirts to allow for unrestricted movement and to prevent clothing from getting tangled on the bar. All could see the bar from the start of the walkway.

Apparatus—Participants were tested on an elevated wooden walkway (4.9 m long $\times$ 0.98 m wide $\times$ 0.64 m high), covered with a blue, vinyl mat (Figure 1A). Two walls (1.91 m high)

defined the horizontal extent of the opening (0.94 m wide). A wooden frame 196 cm above the apparatus held the two walls together. An assistant placed a horizontal bar (1 cm wide, striped, curtain tension rod) between the two walls at heights ranging from 10 cm to 191 cm in 1.0 cm increments. Tape measures along the sides of each wall ensured that the bar was level.

Four video cameras recorded the session. Views from a stationary side camera, a panning side camera, and a stationary back camera captured participants' movements. A measurement camera recorded the presentation height from the tape measure for each trial. The four camera views were mixed into a single digital video file for ease of later coding.

Procedure—First, in the “Over/Under” task, we determined participants' spontaneous action selection for going over and under the bar. Participants stood barefoot at the end of the walkway 2.5 m (approximately 3–4 steps) from the opening. They faced away from the opening at the start of each trial until the experimenter set the bar to the correct height and verbally cued them to turn around and go through the opening. The experimenter instructed them to go over or under the bar in any manner they wished with the caveats that they could not touch the bar (to ensure they took the task seriously), hold onto the side walls (so that performance reflected participants' own capabilities), or run or do a two-footed jump (for safety reasons on the elevated walkway). However, they could rise up on tiptoe or execute a one-footed hop after the leading leg was above the bar. The bar was first presented at 10 cm and 191 cm to familiarize participants with the task. All stepped over the low bar and walked under the high bar with minimal gait modifications. Then, the experimenter adjusted the bar height in a quasi-random order using a psychophysical procedure (similar to that used in Franchak et al., 2012) to estimate two “boundary” bar heights (the “always-over” and “always-under” bar heights) as quickly and efficiently as possible. The *always-over* bar height was the highest bar height the participant always went over. That is, the participant always went over the bar at all lower heights presented, specifically including the next 1- and 2-cm lower bar heights. The *always-under* bar height was the lowest bar height the participant went under. The participant always went under the bar at all higher heights presented, specifically including the next 1- and 2-cm higher bar heights.

Next, in the “Maximum/Minimum Heights” task, we determined the lower and upper boundaries of the *gray zone*—the range of bar heights that allowed *both* going over and under. As in Over/Under, participants began trials 2.5 m from the opening and faced away until the experimenter set the bar to the appropriate height. But in this task, we instructed participants to attempt to go over or under until they failed by touching the bar so that it moved (with the same caveats as in the Over/Under task). Frequently, the bar was dislodged and fell when participants bumped it. However a light touch moved the bar without dislodging it, so we considered the trial to be a failure if the bar moved more than 0.5 cm. To identify the minimum height, the bar was first presented at 30 cm; to identify the maximum height the bar was first presented at the highest successful bar height in the “Over/Under” task. Then the experimenter set the bar at progressively lower or higher heights in 2- to 4-cm increments until participants moved the bar. This process continued until the participant failed twice at a given height and a height 1 cm higher or lower. If the participant succeeded at the preceding height twice, the preceding height was scored as the minimum/maximum

height participants could navigate. For example, if a participant failed twice at both 80 and 81 cm, and succeeded twice at 79 cm, then the maximum height was scored as 79 cm. Order for Maximum/Minimum heights was counterbalanced across participants.

At the end of the session, the experimenter collected measures of participants' body dimensions to determine relations with lower and upper boundaries of the gray zone and transition region. We measured standing height with a stadiometer, weight on a digital scale, and leg length from groin to medial malleolus down the inseam.

Data Coding—Coders scored videos using Datavyu (www.datavyu.org), an open source video coding software that allows frame-by-frame time-locked analysis. A primary coder scored each trial for whether participants went over or under the bar and whether they succeeded (went over/under the bar without displacing it at least 0.5 cm).

The *transition region* was the range of bar heights at which the participant went both over and under the bar. For example, if a participant always went under bar heights of 80 cm and higher and always went over bar heights of 76 cm and lower, but went under the 77-cm bar height and over the 79-cm bar height at least once, then their transition region spanned 3 cm (including the 77-cm, 78-cm, and 79-cm bar heights). Similarly, if a participant always went under bar heights of 80 cm and higher and always went over bar heights of 78 cm and lower, but went both over and under the 79-cm bar height, then their transition region spanned only 1 cm. And if a participant always went under bar heights of 80 cm and higher and always went over bar heights of 79 cm and lower, then there was no observed bar height at which they went both over and under and the transition region was 0 cm. Thus, to calculate transition regions based on the always-under and always-over bar heights, we subtracted 0.5 cm from the always-under bar height and added 0.5 cm to the always-over bar height and then calculated the difference between the two—yielding transition regions of 3 cm, 1 cm, and 0 cm in these three examples, respectively.

The *transition point* is the midpoint between the always-under and always-over bar heights. Note, in cases where the always-under and always-over bar heights were adjacent (e.g., 80 cm and 79 cm), the transition point represented an interpolated bar height that was not tested.

The coder also classified locomotor methods for going over (Figure 1B–D) as *stepping*, *tiptoeing* (going over a height higher than the measured leg length without hopping), or *hopping* (both feet off floor for at least one frame). The coder classified locomotor methods for going under (Figure 1E–G) as *crawling* (both hands and both knees, or torso or buttocks touched the floor), *midway* (any combination of hands or knees on the floor that did not fulfill requirements for crawling), or *bipedal* (hands, knees, buttock, belly, or back did not touch the floor). Crawling occurred on hands and knees or on the belly. Bipedal strategies including walking, ducking, bowing, and squat-walking. A second coder independently scored 25% of each participant's data to ensure inter-rater reliability. Coders agreed on > 99% of variables, $Kappa > .97$, $p < .001$. Disagreements were settled by discussion.

Results and Discussion

Body dimensions varied widely across participants (Table 1). On average, men were larger than women on every measure except leg length, all p s < .05. However, all subsequent analyses controlled for standing height, so all data were collapsed across gender. Figure 2A represents the extent of the gray zone as a proportion of standing height (left-most bar). As shown in the figure, the region in which both going over and under were possible extended from mid-calf to hip height. Participants' gray zones were variable (Table 2), but did not differ by gender. However, body dimensions affected the upper and lower boundaries of the gray zone (Table 3). Standing height was the best predictor of maximum bar height, $r(18) = .83$, $p < .001$, and BMI (body mass index: kg/m²) was the best predictor of minimum bar height, $r(18) = .71$, $p < .001$. Likely, height was a stronger predictor than leg length ($r(18) = .65$, $p = .002$) because participants used strategies—tiptoeing or hopping over the bar—that decreased the importance of leg length. Likely, BMI was a stronger predictor than weight ($r(18) = .62$, $p = .003$), because BMI better reflected the girth of their midsection.

The transition region reflects the span of heights at which participants sometimes went over and sometimes went under the bar. At heights below or above the transition region, participants always went over or under the bar, respectively. The transition point was the midpoint between the always-over and always-under bar heights and served as an estimate of the point where participants switched from going over to going under.

Participants' decisions were remarkably consistent and their transition points were robustly biased: Participants showed a clear preference to go over the bar. Figure 3A shows the transition regions (vertical black lines) and transition points (horizontal red lines) for individual participants normalized to the extent of their gray zone. Transition regions were small, meaning that decisions were highly consistent. In fact, as shown in the figure, the participants represented in bars 7, 10, and 18 had *no transition region* (no vertical black line). For these participants, there were no bar heights that they went both over and under. Thus, we calculated their transition points as the midpoint between adjacent over and under bar heights. Across participants, the size of the transition region ranged from 0.0% to 4.8% ($M = 1.9\%$) of standing height, and from 0.0% to 13.7% ($M = 5.7\%$) of the gray zone. As shown in Figure 2B (left-most bar), the average transition point was 87.1% of the gray zone, and as shown in Figure 3A it was always above the midpoint of the gray zone (range = 66.9% to 101.9% of the gray zone), indicating that decisions were biased toward going over, not split evenly between over and under. For the participants represented in bars 17, 19, and 20 in Figure 3A, their transition regions, and for 19 and 20, their transition points, were outside the gray zone as determined by the Minimum/Maximum task. In these cases, on at least one trial, the participants attempted to go over the bar at a height that exceeded their ability. However, failures (touching the bar, knocking the bar down, grabbing the wall to prevent falling) were rare in the Over/Under task (3.5% of trials), indicating that action selection reflected participants' abilities. This is consistent with previous work showing that adults are accurate perceivers of affordances (Comalli, Franchak, Char, & Adolph, 2013; Franchak et al., 2012; Mark, 1987; Warren & Whang, 1987).

To examine participants' locomotor methods (Figure 1B–G), we analyzed behaviors at the transition point and the surrounding 5 cm above and below the transition point, bar heights

where high levels of variability should occur. Note, participants always stepped over very low barriers and always walked or ducked under very high barriers. Participants displayed all available methods to go over the bar (stepping, tiptoeing, and hopping) and under (crawling, midway combinations, and bipedal ducking or squatting), indicating that each method was a viable action. Some participants used only 1 method for going over (45%) or under the bar (65%), but many used multiple methods for going over (55%) and under (35%).

Experiment 1: Summary

Adults decided whether to go over or under a horizontal barrier blocking their path. Participants' decisions were highly consistent, as indicated by small transition regions, and consistently biased to go over rather than under the bar; all transition points were > 66% of the gray zone. The over-bias was so strong that some participants chose to hop over the bar rather than to duck or crawl under it. Evidently, participants perceived the cost of going under the bar as greater than going over for all bar heights except those near the limits of their ability to go over. Furthermore, participants used a variety of potential methods for going over and under the bar (e.g., crawling, squat walking, ducking), indicating that each method was viewed as a viable action.

Experiments 2–6 were designed to test the role of various factors in influencing the bias to go over the barrier. That is, we treated Experiment 1 as a control study and aimed to lower participants' transition regions and transition points relative to Experiment 1, without radically changing the extent of the gray zone.

Experiment 2: Ankle Weights

Participants' robust bias to go over the bar suggested that they perceived the cost of going over to be less than going under. Perhaps participants favored going over the bar to minimize energetic cost. Indeed, crawling is more energetically costly than walking (Abitbol, 1988; Morrissey, George, & Ayoub, 1985). In Experiment 2, we asked whether increasing the energetic cost of going over would make going under the bar more attractive and lessen the bias to go over. Thus, we tested a new sample of participants wearing ankle weights.

We considered various options for the mass of the ankle weights. Of course extremely heavy ankle weights would make going over the bar much more difficult. But extremely heavy ankle weights would dramatically lower the upper boundary of the gray zone. A consequence of dramatically lowering the top of the gray zone, say to knee level, is to reduce the number of possible strategies for going under the bar. Ducking and squat-walking are impossible at knee height, and crawling would be the only viable strategy. The likely consequence of forcing participants to crawl would be to encourage walking at the top of the dramatically lowered gray zone. Therefore, the transition point would be higher, not lower. Put another way: Extremely heavy ankle weights would have the effect of increasing, not decreasing, participants' over-bias. Thus, we aimed to find an appropriate amount of ankle weight that would make going over the bar more difficult without dramatically changing the size of the gray zone. Note that even relatively light ankle weights substantially increase the metabolic rate of walking (Brown, et al., 2007).

Method

Participants were 10 healthy, young adults (5 women, 5 men) between 18 and 30 years of age ($M = 22.8$), recruited and compensated as in Experiment 1, with similar body dimensions as in Experiment 1, all p s $> .5$ (Table 1). Data were collected and analyzed as in Experiment 1 except that participants wore a 0.91 or 1.37 kg (depending on their body weight) weight on each ankle (on average, 3% of body weight combined). In addition, we measured the maximum height for going over the bar with and without weights for each participant (with weights first). Due to experimenter error, data from 3 participants' maximum height without weights were missing. We therefore ran 3 additional participants who only performed the maximum task with and without the weights, and their data were included only in the analysis comparing maximum height with and without the weights.

Results and Discussion

The ankle weights made going over the bar more difficult, without substantially decreasing the size of the gray zone. Participants displayed lower maximum heights with ankle weights ($M = 47.4\%$ of standing height, $SD = 2.0\%$) compared to without ankle weights ($M = 48.3\%$, $SD = 2.8\%$), $t(9) = -2.50$, $p = .034$, $d_z = .88$.

We found no difference in the upper and lower boundaries (maximum/minimum bar heights) and size of the gray zone between participants in Experiment 1 and 2, all p s $> .9$ (see Table 2 and Figure 2A for these measures as a proportion of participants' standing height). As in Experiment 1, participants were biased to go over the barrier. Transition regions closely matched those found in Experiment 1 (Figure 3B); $p = .43$, $d = 0.30$. The size of the transition region ranged from 0.0% to 6.1% ($M = 2.5\%$) of participants' standing height, and from 0.0% to 17.5% ($M = 7.3\%$) of the gray zone (Figure 2B). Transition points ranged from 68.3% to 92.9% of the gray zone ($M = 84.5\%$), and despite increasing the cost of going over the bar with the ankle weights, participants showed no difference in transition points compared with Experiment 1; $p = .55$, $d = 0.25$ (Figure 2B). The small effect size would have required 514 participants in the two experiments to achieve statistical significance with power of 0.8. Failures did not increase while wearing ankle weights (2.3% of trials). Similar to Experiment 1 participants used all methods for going over and under. A slight majority of participants used only 1 method for going over (60%) or under (70%) the bar. In summary, increasing the energetic cost of lifting the legs to go over the bar with ankle weights did not reduce participants' bias to go over the bar, suggesting that the observed bias was not due to energetic cost alone.

Experiment 3: Soft Surface

Experiment 3 was designed to decrease the potential cost of going under the bar. Perhaps participants' over-bias was due to the discomfort of crawling under the bar. So we aimed to make crawling more comfortable by putting high-density foam padding over the wooden surface. To ensure the validity of this manipulation, we asked 10 naïve participants to crawl five times over the padded surface and five times over the wooden surface used in Experiment 1 (order counterbalanced). After each block of five trials, participants rated crawling comfort on a 5-point scale, from very uncomfortable (1) to very comfortable (5).

Every participant rated the padding as more comfortable ($M = 3.9$, $SD = 0.88$) than the wooden surface ($M = 2.1$, $SD = 0.57$), $t(9) = 9.00$, $p < .001$, $d = 3.17$. In addition, the pliable padded surface presumably made upright balance more challenging, which should incentivize going under the bar and lower the transition point.

Method

We tested 10 new participants, all healthy, young adults (6 women, 4 men) between 18 and 27 years of age ($M = 20.82$), recruited and compensated as before. Body dimensions were similar to Experiment 1 (Table 1); all p s $> .1$. Data were collected and analyzed as in Experiment 1 except that high-density foam padding topped by a shag carpet was placed on the wooden walkway under the blue mat.

Results and Discussion

We found no difference in the maximum or minimum bar heights or size of the gray zone between participants in Experiment 1 and 3, all p s $> .4$ (Table 2 and Figure 2A). The transition region closely matched Experiment 1 ($p = .31$, $d = 0.38$) and ranged in size from 0.6% to 6.8% of standing height ($M = 2.5\%$) and from 1.7% to 19.4% of the gray zone ($M = 7.6\%$) (Figure 2B). Transition points were high, ranging from 70.2% to 96.2% of the gray zone ($M = 85.5\%$). We found no difference in transition points compared with Experiment 1, $p = .67$, $d = 0.17$. Given the small effect size, we would have required 1130 participants in the two experiments to achieve statistical significance with power of 0.8. Despite the padding, which was designed to ease the discomfort of crawling under the bar, participants' bias to go over the bar persisted, indicating that factors other than comfort were at play. Moreover, the frequency of crawling did not increase relative to Experiment 1. Participants used the same range of locomotor methods. About half of participants used multiple methods for going over (50%) or under (40%) the bar. As before, failures were rare (4.0% of trials).

Experiment 4: Ending in a Crawling Position

Experiment 4 was designed to increase the cost of staying upright to go over the bar by forcing participants to assume a crawling posture directly after going through the opening. Because the weights and padded surface used in Experiments 2 and 3 did not alter participants' over-bias, we speculated that the bias is not rooted in the physical exertion or comfort of performing the action. However, in Experiments 1–3, participants stood up or remained upright when they passed over/under the bar so that they could walk back to the starting platform. Possibly, participants recognized that the next action after passing the bar involved walking back to the beginning of the platform at the end of the trial. Adults regularly plan for their end state posture—by enduring an awkward initial state to ensure a comfortable end state during implementation—when performing manual (Rosenbaum et al., 2012) and locomotor actions (Cowie et al., 2010). For example, adults use an awkward thumb-down grip to pick up an overturned glass so that the end-state has a comfortable and stable thumb-up grip for filling the glass with water (Rosenbaum, et al., 1990).

Therefore we tested whether the bias to go over would remain if participants were required to get down on their hands and knees directly after passing through the opening. We hypothesized that if participants were biased to go over the bar because they were planning to walk back to the starting platform, then if their next action involved the crawling posture, they should be willing to go under the bar. In Experiment 4, participants' task was to retrieve a ball from a bin on the floor just past the doorway. Because the bin height was lower than the walkway, it was impossible to retrieve the ball without getting down on hands and knees. If participants considered their posture in terms of the entire task and planned actions accordingly, they should be biased to go under the bar in preparation of grabbing the ball from the bin.

Method

We tested 10 new, healthy, young adults (6 women, 4 men) between 19 and 27 years of age ($M = 21.04$), recruited and compensated as before, with similar body dimensions as in Experiment 1; all p s $> .1$ (Table 1). The apparatus was set up as in Experiment 3 except the shag carpet was removed and a bin filled with ping pong balls was placed on the floor just past the barrier. The procedure was identical as before with the additional instruction to retrieve a ball from the bin after navigating the bar.

Results and Discussion

We found no difference in the maximum and minimum bar heights or size of the gray zone between participants in Experiments 1 and 4, all p s $> .1$ (Table 2 and Figure 2A). As shown in Figure 2, transition regions ranged from 0.0% to 6.2% of standing height ($M = 3.0\%$) and 0.0 % to 23.9% of the gray zone ($M = 9.9\%$). A t -test comparing Experiments 1 and 4 on the size of transition region as a percentage of the gray zone trended towards significance, $t(28) = -1.95$, $p = .062$, $d = 0.68$ (Figure 2B). However, ending in a crawling posture failed to eliminate participants' bias to navigate over the bar. Transition points were still high in the gray zone ranging from 70.5% to 97.3% of the gray zone ($M = 84.7\%$) as in previous experiments. There was no difference in the height of the transition point as a percentage of the gray zone between Experiments 1 and 4, $p = .54$, $d = 0.24$. Given the small effect size, 530 participants would have been required in the two experiments to achieve statistical significance with power of 0.8. Failures were rare (3.8% of trials). As before, participants used all three methods for going over the bar, but they never used bipedal methods to go under. About half of the participants used multiple methods to go over (60%) or under (40%) the bar.

The task of retrieving a ball required a crawling posture directly after participants passed through the doorway. We predicted that if participants planned their movements with this ending posture in mind they would go under the bar more frequently than in Experiment 1. But they did not. Transition points were not lower when their next action required crawling. However, participants' transition regions trended toward being larger than in Experiment 1—suggesting less confidence or assuredness in action selection compared with Experiment 1. The fact that no participant went under the bar using a bipedal method suggests that participants were planning ahead while passing under the bar.

Experiment 5: Starting in a Crawling Position

Experiment 5 was designed to decrease the cost of going under the bar. Although ending posture did not influence transition points, perhaps starting participants in a crawling posture would do so. We instructed participants to start each trial in a crawling posture so that going over the bar would require a change in posture whereas going under would not.

Method

We tested 10 new, healthy, young adults (6 women, 4 men) between 19 and 29 years of age ($M = 22.3$), recruited and compensated as before with body dimensions similar to those in Experiment 1, all p s $> .3$ (Table 1). The apparatus was identical to Experiment 4 but we removed the bin and balls. The procedure was identical to Experiment 1 except that participants started each trial in a crawling posture on the walkway approximately 1 m away from the bar instead of standing at the beginning of the walkway. To ensure that participants were not biased by seeing the bar being placed at each height, a curtain blocked their view of the opening until the experimenter removed it and the trial began.

Results and Discussion

We found no difference in maximum or minimum bar heights or the size of the gray zone between participants in Experiments 1 and 5, all p s $> .3$ (Table 2 and Figure 2A). However, for the first time, we found differences in participants' decisions about how to navigate the bar compared with Experiment 1. Transition regions ranged from 1.2% to 7.3% of standing height ($M = 3.2\%$) and 3.7% to 26.7% of the gray zone ($M = 10.4\%$). A t -test comparing Experiments 1 and 5 on the size of transition region as a percentage of the gray zone was significant, $t(28) = -2.18$, $p = .038$, $d = 0.76$ (Figure 2B). Transition points in Experiment 5 ($M = 79.3\%$ of the gray zone, $SD = 7.1\%$) were lower than those in Experiment 1 (Figure 2B), $t(28) = 2.17$, $p = .039$, $d = 0.89$. Nonetheless, starting in a crawling posture failed to completely eliminate participants' over-bias; transition points ranged from 72.1% to 92.0% of the gray zone. As before, failures were rare (2.8% of trials). When going over the bar, 40% of participants used multiple methods, but no participant used multiple methods to go under; they always crawled. In fact, 30% of participants maintained their starting posture and crawled over the lowest height (16 cm) on hands and knees—providing additional evidence for a desire to remain in the current posture.

Starting participants in a crawling position lowered their transition points and made crawling their strategy of choice for going under, but the bias to go over remained. In fact, participants stood up to go over the bar, even if it was above their head at the start of the trial. A few participants stood up to view a bar above their head and then returned to a crawling position to go under. The bias to go over the bar appears powerful and pervasive in adults.

Experiment 6: Children Going Over or Under a Barrier

Experiment 6 was designed to reduce the social cost of going under the barrier. Across experiments, adults showed a robust over-bias that was apparent even when the cost of going under was reduced and the cost of going over was increased. Participants showed the greatest reduction in over-bias when starting in a crawling posture, but the over-bias remained.

Several participants in Experiments 1–5 mentioned that they felt self-conscious in a crawling posture. Thus, we considered the possibility that adults were biased to go over the bar because they felt embarrassed to crawl due to social conventions. We reasoned that children are less inhibited and may not adhere to social norms that make adults reticent to crawl. Thus, we tested a sample of children as in Experiment 1.

Methods

Participants were 20 healthy children (9 girls, 11 boys) between 5 and 6 years of age ($M = 5.7$). Given that we had no baseline experiment with children and thus no way to estimate their variability, we used the same sample size as in Experiment 1. Families were recruited from a pool of parents who had expressed interest in participating in developmental studies, and received a photograph magnet and tote bag as souvenirs of participation. Body dimensions—excluding leg length because children were not able to comply with instructions—were recorded as in Experiment 1 (Table 1). Children were tested and their data analyzed as in Experiment 1. We covered the wooden surface with the foam padding (as in Experiments 4 and 5) to ensure children's safety because pilot data showed that children dropped straight onto their knees or flung themselves forcefully to the ground.

To ensure that children understood and remembered the rules (no running, touching the wall, or touching the bar), we asked them to restate the rules before each task. Children received a sticker after repeating the rules the first time and after every task to maintain their interest and desire to follow the rules of the game.

Results and Discussion

As expected, children's body dimensions were smaller than the adults in Experiment 1, all p s $< .001$ (Table 1). However, we were surprised to find that children's maximum bar height comprised a smaller proportion of their standing height, meaning that they were less capable at going over a high bar. Furthermore, the minimum bar height comprised a larger proportion of their standing height, meaning they were less capable of crawling under the bar. Thus, the size of their gray zone comprised a smaller proportion of standing height compared with those of adults in Experiment 1, all p s $< .001$ (Table 2 and Figure 2A).

Transition regions ranged from 0.9% to 19.2% of standing height ($M = 7.3\%$) and 4.5% to 72.4% of the gray zone ($M = 32.1\%$). The size of children's transition region was more variable than those of adults in Experiment 1, so we did not assume equal variances when comparing them. As shown by the large vertical line in Figure 2B, children displayed substantially larger transition regions than adults in Experiment 1, $t(20.8) = -5.90$, $p < .001$, $d = 1.86$. Although the average transition point ($M = 71.5\%$) was lower than those of adults in Experiment 1, $t(23.5) = 2.25$, $p = .034$, $d = 0.71$, children's transition points were also highly variable—ranging from the bottom (5.9%) to the top (110.3%) of the gray zone (Figure 3F)—with individual children producing transition points far lower and higher than those produced by adults.

We classified children's strategies for going over the bar as stepping or hopping, and they did both. Children went under the bar by crawling or midway methods and one child used a

bipedal method on one trial. Children rarely used multiple methods to go over (10%) or under (20%) the bar.

Children were much more variable in their decisions than adults, both within and between individuals. Many children had large transition regions that spanned most of their gray zones, and several had narrow transition regions. However, their decisions were not entirely random (i.e., their transition region did not span the entire gray zone). This diversity in action selection resulted in lowering the transition point. Although children were biased to go over the bar on average, 20% of children displayed transition points below 50% of their gray zone and 30% had transition points lower than any adult in Experiments 1–5.

General Discussion

Six experiments investigated how adults and children select one action among possible alternatives based on their decisions to go over or under a horizontal bar at varying heights. Experiments 1–5 showed that adults were consistently biased to go over a bar they could easily go under. Adults only treated the two options as equivalent near the limits of their ability to go over. Adults chose to go over despite wearing ankle weights that required more force to lift the leg (Experiment 2), being tested on a padded surface that made crawling more comfortable (Experiment 3), being forced to end in a crawling posture after passing through the doorway (Experiment 4), and starting in a crawling position (Experiment 5). However the over-bias in Experiment 5 was slightly reduced. Experiment 6 showed that children behaved very differently from adults. Some children preferred to go over and some under the bar, and decisions were highly inconsistent.

The Gray Zone

Previous work assessed walkers' perception of possibilities for action—affordances—based on whether a particular action was possible or impossible (e.g., Franchak et al., 2012; Stefanucci & Geuss, 2010; van der Meer, 1997; Warren, 1984; Warren & Whang, 1987). Regardless of how accurately people perceive affordances, the ability—or lack thereof—to produce an action is consistent (Comalli et al., 2013; Franchak et al., 2012; Mark, 1987). Generally, an action is either possible or not, meaning that the affordance function has a steep slope (Franchak & Adolph, 2014). Therefore, accurate decisions to attempt a specific action have a narrow region of ambiguity—decisions are yes or no, black or white.

The current experiments examined decisions among possible actions in a relatively large action space, what we call a “gray zone,” where all decisions are correct and multiple choices are possible. Participants selected one of two large-scale actions—going over or under a bar blocking their path—and selected which of multiple methods to do so. Thus, our gray zone for going over and under contained other gray zones for specific locomotor strategies. For example, crawling under the bar was also possible when participants used midway or bipedal methods. And tiptoeing and hopping over the bar were possible when participants used stepping. But, when hopping was required to go over the bar, stepping was not possible. When crawling was required to go under, squat-walking and ducking were not possible. So, a gray zone in which two large-scale actions are possible—in this example,

going over and under—contains shades of gray where different numbers of sub-actions are possible.

Consistency and Bias in Action Selection

Adults' action selection was consistent and biased. Intraindividual variability was uniformly low—all adult participants displayed variable decisions only within a narrow transition region—and interindividual variability was low. Across Experiments 1–5, the transition region occupied about 7% of the gray zone, or about 4 cm. For every adult in Experiments 1–5, the transition point was at least 66% of their gray zone and for 70% of adults, the transition point was between 75% and 85% of their gray zone. We attempted to alter adults' over-bias in several ways, but were largely unsuccessful. We slightly reduced the bias by starting adults in a crawling posture, suggesting that the over-bias was partially explained by a reluctance to change the current posture. Indeed, some adults crawled—rather than stood up and walked—over the bar when it was very low.

Adults factor the penalty for error into their motor decisions such that more costly penalties have a larger influence on action selection (Trommershäuser, Maloney, & Landy, 2008; Comalli, et al. 2013). The penalty for failure while going over the bar was the risk of tripping, falling off the raised platform, and knocking down the bar. The penalty for failure while going under the bar was bumping or displacing the bar. Presumably, tripping or falling was a greater cost to participants than dislodging the bar. Previous findings show that older adults, young adults, and 17-month-old infants are more conservative in deciding whether to navigate a narrow ledge compared to squeezing through a narrow doorway because they consider falling to be a more severe penalty than entrapment (Comalli et al., 2013; Franchak et al., 2012). If the consequences of failure were a primary factor in action selection, participants in the current experiments would have been biased to go under, not over. However, failures were rare and were not an important factor in participants' decisions.

Navigating under the bar may have been more energetically costly than going over. Strategies for going over involved stepping, tiptoeing, and hopping which required dynamic balance and strength to launch over the barrier on one leg (Granacher, Gollhofer, & Kriemler, 2010). Strategies for going under involved ducking, squatting, and crawling. Participants had to crouch low to squat or completely readjust posture to put hands and knees on an uncomfortable, hard surface (Experiments 1 and 2). If participants were biased to go over the bar because it was less energetically costly than going under, the bias should have been reduced when we made going over more difficult. Despite additional energetic cost from ankle weights in Experiment 2, participants were just as biased to go over the bar as without the weights. Another possibility was that crawling under the bar was physically uncomfortable on a hard, wooden surface. However, padding the walkway with foam and shag carpet made crawling more comfortable, but it did not reduce participants' bias to go over the bar.

In Experiment 4, participants ended each trial on all fours. If physical changes did not affect decisions, perhaps a goal to end comfortably would encourage participants to change their actions and go under the bar to more easily assume the end posture. Numerous studies show that adults endure an uncomfortable start state to enable a smooth transition to a comfortable

end state (Rosenbaum et al., 2012). Furthermore, children and adults plan their stepping movements to end in a comfortable walking position (Cowie, Smith, & Braddick, 2010). However, requiring participants to end in a crawling position did not reduce their bias to go over the bar in an upright position. Their over-bias outweighed planning for future actions.

Another possibility for the observed bias was that participants did not want to change out of their upright starting posture. We tested this possibility in Experiment 5, where participants started each trial in a crawling posture. Although this manipulation did significantly lower transition points compared to Experiment 1, the over-bias was still evident. Even when starting in a crawling position with a bar above their heads, adults frequently stood up to walk over the bar. Therefore, starting posture only partially accounted for the strong bias to go over the bar. The tendency to maintain the current locomotor posture is not limited to going over and under a bar. When the choices for action are as mundane as navigating through or around a narrow aperture, adults choose to minimize changes to the current locomotor posture. They walk straight through apertures if they do not need to turn their shoulders, but they detour around the obstacle if shoulder turning is required (Hackney & Cinelli, 2013b; Hackney et al., 2013).

Results of Experiment 6 with children indicate that bias in motor decisions might be influenced by psychological factors such as embarrassment. Avoiding embarrassment can lead adults to select actions that are not optimal. For example, adults are willing to incur higher monetary costs in exchange for preventing the public from learning about embarrassing tasks they perform (Brown, 1970). Indeed, several adult participants mentioned feeling embarrassed to crawl. Young children frequently crawl during play, so we reasoned that they would not be embarrassed to crawl under the bar. We hypothesized that if embarrassment were a driving factor in adults' bias to go over then children should display transition points more in the center of the gray zone. Children had significantly lower transition points than adults and seemed perfectly happy to crawl under the bar—a third had transition points less than 60% of their gray zone.

A related point concerns the everyday use of various postures. Walking is more familiar and habitual for adults than crawling and this familiarity may have contributed to the bias in action selection. In contrast, crawling is more common in young children and thus makes them less biased to walk. Future studies should examine whether participants remain consistent in their decisions and have a preference for maintaining their current posture while keeping the familiarity of the alternative postures consistent (e.g., walking to the left or right of a pillar that is placed at various locations in horizontal space).

Compared with adults, children were hugely inconsistent, showing high levels of intraindividual variability and dramatic individual differences in action selection. We considered the possibility that children's performance was inconsistent because they did not take the task seriously or did not try to follow the rules of the task. In fact, 4 of 20 children had transition points outside their gray zone, compared with only 2 of the 60 adults in Experiment 1–5. However, children only failed on 10% of trials, they never failed on baseline trial heights, and they seemed genuinely apologetic if they touched the bar.

We see a similar compression in variability from children to adults in a range of tasks (Comalli et al., 2016; Scharoun & Bryden, 2013; Thibaut & Toussaint, 2010; Wunsch, Henning, Aschersleben, & Weigelt, 2013). Adults produce highly consistent behaviors when tasked with grasping a hammer to pound a peg or a glass to fill it with water (Comalli et al., 2016; Scharoun & Bryden, 2013). Adults' locomotor decisions are equally consistent (Hackney & Cinelli, 2013b; Hackney et al., 2013). Children, in contrast, are inconsistent from trial to trial when selecting among multiple actions (Comalli et al., 2016; Hackney & Cinelli, 2013a; Keen, Lee, & Adolph, 2014), perhaps because variability allows for exploration, which can inform on the most efficient or comfortable action to perform in various situations.

Conclusion

How is one action selected from an array of possible actions? The current studies show that adults' action selection for locomotion is highly consistent and strongly biased toward using an upright posture, despite various added costs to remaining upright. However, a reluctance to change from the current posture—even a crawling posture—weakens the bias to stay upright. Young children do not display adult-like consistency in action selection or the robust bias to remain upright. These aspects of action selection must be forged over development.

Acknowledgments

This research was supported by National Institute of Health and Human Development Grant R37-HD033486 to Karen E. Adolph and by a grant from the New York University Dean's Undergraduate Research Fund to Dhandevi Persand.

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Figure 1.

Walkway apparatus, procedure in the “Over/Under” task, and various methods for going over and under a horizontal bar impeding the path of locomotion. (A) Participants started each trial on a raised walkway, with their back to the opening. The trial began when the experimenter prompted the participant to turn around and approach the opening. Participants decided whether to go over or under each bar height. Coders classified locomotor methods for going over as (B) stepping, (C) tiptoeing (going over a height higher than the measured leg length without hopping), and (D) hopping (both feet off floor for at least one frame). Coders classified methods for going under as (E) crawling (both hands and both knees, or torso or buttocks touched the floor), (F) midway (any combination of hands or knees on the floor that did not fulfill requirements for crawling), and (G) bipedal (hands, knees, buttock, belly, or back did not touch the floor). Crawling occurred on hands and knees or on the belly. Bipedal strategies including walking, ducking, and squat-walking.

Figure 2.

Summaries of average transition regions and transition points for Experiments 1–6 represented as (A) a percentage of participants' standing height and (B) a percentage of their gray zone (the range of bar heights where participants could go both over and under the bar). The cartoon figure in (A) represents participants' average standing height. The size of the gray bars in (A) shows that the adults in Experiments 1–5 had gray zones that spanned from mid-calf to hip height. Compared with adults, the children in Experiment 6 had smaller gray zones with lower boundaries closer to the knee and upper boundaries closer to mid-thigh. In both (A) and (B), the horizontal red lines represent the average transition point (the estimated height where participants transitioned from going over to under the bar), the vertical black lines represent the average extent of the transition region (the range of bar heights where participants chose to go both over and under), and the black horizontal lines represent the boundaries of the gray zone. Only Experiments 5 and 6 produced significantly lower transition points than Experiment 1, both p s < .04.

Figure 3.

Individual participants' transition points and transition regions as a percentage of their gray zone (the range of bar heights where participants could go both over and under the bar) in Experiments 1–6. The horizontal red lines represent participants' transition points (the estimated height where participants transitioned from going over to under the bar), and the vertical black lines represent the transition regions (the range of bar heights where participants chose to go both over and under). Adults (Experiments 1–5) were highly consistent in their decisions (as indicated by their small transition regions) and were consistently biased to go over the bar (as indicated by all transition points above 66% of their gray zone). Children (Experiment 6) were highly inconsistent in their decisions (as indicated by their large transition regions) and they did not show a consistent bias to go over the bar (transition points spanned the entire range of the gray zone).

Table 1**Body Dimensions of Participants in Experiments 1–6**

	Experiment 1	Experiment 2	Experiment 3
Height (cm)			
Minimum	152.0	156.0	147.7
Maximum	185.3	180.5	177.9
Mean	166.9	169.0	164.1
Weight (kg)			
Minimum	47.9	47.1	36.0
Maximum	84.0	78.7	70.6
Mean	64.0	63.6	58.1
BMI (kg/m²)			
Minimum	17.6	18.2	16.5
Maximum	28.2	25.8	24.4
Mean	22.9	22.2	21.4
Leg length (cm)			
Minimum	58.7	64.6	60.9
Maximum	78.4	77.4	76.1
Mean	68.8	70.0	66.5
	Experiment 4	Experiment 5	Experiment 6
Height (cm)			
Minimum	147.7	154.4	105.9
Maximum	184.4	175.6	120.0
Mean	168.6	164.9	112.2
Weight (kg)			
Minimum	55.1	53.4	16.1
Maximum	98.7	70.4	22.8
Mean	70.7	61.3	19.1
BMI (kg/m²)			
Minimum	19.0	20.2	13.1
Maximum	31.9	24.3	18.2
Mean	24.7	22.5	15.3
Leg length (cm)			
Minimum	60.8	63.6	n/a
Maximum	76.0	70.6	n/a
Mean	68.0	67.0	n/a

Height = from top of head to bottom of feet, with participants standing against a stadiometer

Weight = barefoot and dressed in tights and t-shirt, with participants standing on a digital scale

BMI (body mass index) = (body weight in kg)/(height in m)²

Leg length = from crotch to ankle (medial malleolus) along the inseam of the tights

Note, descriptive statistics were averaged over males and females.

N s = 20 for Experiment 1, 10 for Experiments 2–5, and 20 for Experiment 6.

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Table 2

Gray Zone Represented as a Percentage of Standing Height for Experiments 1–6

	Experiment 1	Experiment 2	Experiment 3
Gray Zone			
Minimum	0.28	0.30	0.26
Maximum	0.40	0.38	0.41
Mean	0.33	0.34	0.33
Lower Limit			
Minimum	0.12	0.12	0.14
Maximum	0.18	0.18	0.21
Mean	0.14	0.15	0.17
Upper Limit			
Minimum	0.41	0.44	0.32
Maximum	0.49	0.51	0.46
Mean	0.46	0.47	0.39
	Experiment 4	Experiment 5	Experiment 6
Gray Zone			
Minimum	0.26	0.27	0.13
Maximum	0.36	0.38	0.30
Mean	0.32	0.32	0.23
Lower limit			
Minimum	0.12	0.12	0.14
Maximum	0.18	0.18	0.21
Mean	0.14	0.15	0.17
Upper limit			
Minimum	0.41	0.44	0.32
Maximum	0.49	0.51	0.46
Mean	0.46	0.47	0.39

Note, descriptive statistics were averaged over males and females.

Ns = 20 for Experiment 1, 10 for Experiments 2–5, and 20 for Experiment 6.

Table 3

Experiment 1: Correlation Matrix of 4 Measures of Body Dimensions, Size of the Gray Zone, and Lower and Upper Boundaries of the Gray Zone

	1(Ht)	2(Wt)	3(BMI)	4(Leg)	5(Min)	6(Max)
1 Height	1					
2 Weight	.72**					
3 BMI (kg/m ²)	.16	.80**				
4 Leg length (cm)	.80**	.54*	.09			
5 Min Height (cm)	.22	.62**	.71**	.17		
6 Max Height (cm)	.83**	.45*	-.08	.65**	.13	
7 Gray Zone (cm)	.76**	.26	-.29	.59**	-.17	.96**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Gray Zone = the range of bar heights that participant could both go over and under

Min Height = lower boundary of the gray zone, lowest bar height that participant could go under

Max Height = upper boundary of the gray zone, highest bar height that participant could go over

Note, the size of the gray zone and the upper and lower boundaries of the gray zone were determined in the "Minimum/Maximum" task.