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RESEARCH ARTICLE

Perception of passage through openings depends on the size of the body in motion

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Abstract Walkers need to modify their ongoing actions to meet the demands of everyday environments. Navigating through openings requires gait modifications if the size of the opening is too small relative to the body. Here we ask whether the spatial requirements for navigating horizontal and vertical openings differ, and, if so, whether walkers are sensitive to those requirements. To test walkers' sensitivity to demands for gait modification, we asked participants to judge whether they could walk through horizontal openings without shoulder rotation and through vertical openings without ducking. Afterward, participants walked through the openings, so that we could determine which opening sizes elicited gait modifications. Participants turned their shoulders with more space available than the space they left themselves for ducking. Larger buffers for horizontal openings may reflect different spatial requirements created by lateral sway of the body during walking compared to vertical bounce. In addition, greater variability of turning from trial to trial compared with ducking may lead walkers to adopt a more conservative buffer to avoid errors. Verbal judgments accurately predicted whether openings required gait modifications. For horizontal openings, participants' judgments were best predicted by the body's dynamic abilities, not static shoulder width. The differences between horizontal and vertical openings illustrate that walkers account for the dynamic properties of walking in addition to scaling decisions to body dimensions.

Keywords Locomotion · Walking · Apertures · Affordances · Gait modifications

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Introduction

Walking is an automatized action with a repeating pattern, but people do not walk the same way all the time. To meet the demands of the everyday environment, walkers must continually modify their ongoing actions, turning to slip through a partially closed doorway or ducking to avoid a low-hanging branch. Gait modifications involve changes in the overall configuration of the body, the position of the limbs, and the speed and amplitude of locomotor movements—alterations that make walking flexible and adaptive. Whether gait modifications are necessary depends on the affordance relation—the fit between the body and the environment (Gibson 1979).

Walking through openings is a commonly used paradigm for studying affordances, partly because of the straightforward relation between body dimensions and opening size: Whether walkers need to turn or duck depends on the size of the opening relative to the size of the body. Indeed, walkers modify their gait to pass through openings based on the size of the opening relative to their shoulder width or standing height, regardless of absolute opening size. Both broad- and narrow-shouldered adults turn to pass through horizontal openings 1.2–1.3 times their shoulder widths (Warren and Whang 1987; Higuchi et al. 2006). Similarly, both tall and short adults duck to pass under barriers 1.00–1.04 times their heights, and they maintain this ducking ratio when their height is altered experimentally with a helmet or platform shoes (van der Meer 1997; Stefanucci and Geuss 2010). Even infants turn and duck in accordance with the space available for their bodies (Comalli and Adolph in prep; Franchak and Adolph 2012), demonstrating that people adapt their movements according to the spatial demands created by body size.

Previous researchers have reported that walkers modify their gait to incorporate a so-called safety margin—a

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"buffer" space beyond body size—for both horizontal (Warren and Whang 1987) and vertical openings (van der Meer 1997). In other words, walkers scale gait modifications to the relevant body dimension, but give themselves a small cushion of extra space to avoid colliding with the sides or top of the opening: They turn and duck at ratios greater than 1.0 times their shoulder width and standing height. Describing this space with the term "safety margin," however, implies that the extra space represents walkers' caution or a margin of error by which walkers overestimate the spatial requirements for passage. In this paper, we adopt the neutral term "buffer," which is agnostic about these different connotations.

Walkers adjust their buffer space in response to task demands. For example, walkers turn (Warren and Whang 1987) at larger openings when walking at faster speeds and when running (Higuchi et al. 2011). There are two interpretations for why walkers adapt the buffer space when walking speed increases. First, walkers may be more careful when moving more quickly because a high-speed collision presumably incurs a greater cost compared to brushing the shoulders at a slower speed—larger buffers might imply greater caution (a true safety margin). Second, faster movement induces greater lateral sway of the body, which presumably requires a larger buffer space to prevent collision—larger buffers might reflect increased spatial requirements for passage.

Horizontal and vertical openings

In this paper, we extend previous research by asking whether buffer space is tuned to the specific spatial requirements of different types of actions by comparing buffers for fitting through horizontal and vertical openings. That is, how do different body–environment relations—different affordances—determine the spatial requirements for passage? We compared affordances for walking through horizontal and vertical openings because these tasks have been studied extensively in previous work. Horizontal and vertical openings pose the same question to walkers: Does the opening require gait modification? However, each type of opening entails different modifications, different penalties for error, and different limiting factors; thus, buffers may differ for each type of opening. Previously reported values for turning (Warren and Whang 1987; Higuchi et al. 2006) and ducking ratios (van der Meer 1997; Stefanucci and Geuss 2010) suggest that buffers do differ; however, they have not been directly tested in a within-subjects design.

Horizontal and vertical openings demand different body configurations to accommodate physical constraints. To pass through a narrow opening, walkers must turn their shoulders. With decreasing opening widths, walkers must increase their shoulder rotation (Fath and Fajen 2011; Higuchi et al. 2011), to the point where they must turn their bodies completely to the side to squeeze through (Franchak et al. 2010). To walk under a barrier, people must duck their heads. With lower barrier heights, people often combine ducking with bending their knees or bending at the waist. The relative ease and smoothness of these adaptations might influence walkers' readiness to modify their gait for each type of opening.

Failure to modify gait appropriately yields different penalties for horizontal and vertical openings: Failing to turn results in bumped shoulders; failing to duck results in a bumped head. With increased penalties for error, walkers are less willing to attempt to walk without gait modification. For example, walkers judge that they would duck for higher barriers when the barrier is made of metal than when the barrier is made of foam (Wagman and Malek 2009). People are generally more reluctant to hit their heads than their shoulders, so they might perceive a greater penalty and allow themselves more space for vertical compared with horizontal openings. If buffer space does depend on the penalties for error, then "safety margin" may in fact be the more appropriate term.

Affordances for fitting through horizontal and vertical openings are limited by shoulder width and standing height, respectively. However, the dynamics of walking also determine spatial need: Walking involves horizontal and vertical oscillations—lateral sway and vertical bounce—in addition to forward movement. In healthy adults, unrestricted walking (with no horizontal or vertical barriers) generates an average of 6–7 cm of lateral swaying movements of the shoulders from side to side such that the moving body takes up more horizontal space than the width of the shoulders—about 3.5 cm on each side (Murray et al. 1964; De Bujanda et al. 2004). Walking also generates vertical bouncing movements of the body up and down: During the swing phase, as the swinging leg passes the supporting leg, the body is at its highest point—roughly standing height—but during the stance phase with both feet on the ground, the body dips by 4–5 cm to its lowest point (Murray et al. 1964; Waters et al. 1973). These swaying and bouncing motions are different in nature and degree; thus, they might affect demands for space differently for each dimension.

Affordances have typically been divided into two categories: action-scaled and body-scaled (Fajen et al. 2008). Action-scaled affordances depend on the dynamics of the body. For example, walkers choose to ascend steps of a preferred height that minimizes their own energy expenditure (Warren 1984). Moreover, leaping height and distance depend on explosive forces used to propel the body (Cole et al. under review; Weast et al. 2011). In contrast, affordances for passing through openings have been almost exclusively described as body-scaled, that is, determined by the width of the shoulders and the height of the body. However, if affordances for passage depend on different oscillations in horizontal and vertical dimensions, we would argue that walking through apertures is action-scaled, not body-scaled. Of course, the dynamics of the body depend on the size of the body. However, the term "body-scaled" implies that the affordance depends on the static size of the body, not the dynamic size of the body in motion.

Verbal judgments and gait modifications

If we find that different actions for navigating openings entail different buffer spaces, a second question is whether walkers are sensitive to the different spatial requirements prior to acting. Evidence for the accuracy of prior judgments is different for turning and ducking. Some research suggests that when standing at a distance, walkers judge that they would turn for openings 1.16 times their shoulder widths, a smaller ratio compared to when they actually walk through, 1.2–1.3 times their shoulder widths (Warren and Whang 1987; Wraga 1999; Wagman and Taylor 2005). In contrast, walkers judge they would duck for openings 0.98–1.02 times their heights (Wagman and Malek 2008; Wagman and Malek 2009; Stefanucci and Geuss 2010), more closely matching the ratio at which they actually duck, 1.00–1.04 times their heights (van der Meer 1997; Stefanucci and Geuss 2010).

Perceptual judgments of gait modifications have been most often discussed in terms of geometric, body-scaled judgments, that is, whether judgments match the relevant body dimension—shoulder width or height. Focusing on static body dimensions is reasonable because there is an evidence that observers have access to perceptual information that specifies opening size relative to body size. Eye height (the point where the observer's gaze intersects with the visible horizon or the implicit horizon determined by optic flow) can provide information about both horizontal and vertical dimensions relative to the walker's body (Mark 1987; Warren and Whang 1987; Wraga 1999).

However, if buffers differ for different affordances, judgments prior to attempting passage would accurately predict demands for gait modifications only if walkers took into account the buffer space required for that action. But if walkers' judgments are based purely on body-scaled information from eye height, prior judgments will not match actual gait modifications as closely. Information about the dynamics of the body in motion may be necessary for judging spatial needs.

In previous studies, researchers determined the accuracy of verbal judgments about gait modifications by relating each to body dimensions. But, no previous work has directly compared walkers' judgments to their actual actions. In the current study, we compared walkers' verbal judgments to their gait modifications as well as to their body dimensions to determine whether prior judgments account for different buffers, or whether judgments are more closely scaled to static body dimensions.

Current study

The primary aim of the current study was to determine whether buffer spaces required for walking through openings are action-specific. If so, we asked whether walkers perceive openings solely in terms of static body size or whether they also take into account the dynamic size of the body while walking. We compared verbal judgments and gait modifications for horizontal and vertical openings to determine how the factors affecting demands for space influence perception and action.

Participants first judged whether they could walk through horizontal openings without turning their shoulders and whether they could walk through vertical openings without ducking. Next, they walked through openings of varying width and height. We assessed judgments before action performance to prevent motor experience from affecting judgments, as we have demonstrated in the previous work (Franchak et al. 2010). Finally, we measured shoulder width and standing height to compare verbal judgments and gait modifications with relevant body dimensions.

We measured thresholds for verbal judgments and gait modifications in each condition and calculated threshold-to-body ratios to assess intrinsic body scaling. In addition, we calculated the buffer (difference between threshold and body dimension) in centimeters to describe the actual space requirements for each type of opening. Although ratios and buffers are similar measures, we include both because relative spatial requirements could potentially differ from absolute spatial requirements, and because both measures have been widely reported in the literature. In addition, variability of each participant's responses provided a measure of precision of verbal judgments and gait modifications in each condition. If demands for gait modification differ for horizontal and vertical openings, buffer space for turning and ducking should differ. If we establish this difference, we can ask whether verbal judgments scale to body dimensions or, like gait modifications, take both body size and body motion into account.

Method

Participants

We recruited 24 college-aged adults (12 men and 12 women) through the departmental subject pool and offered course credit as compensation. One additional participant completed the study but was excluded for failure to follow experimental instructions. All had normal or corrected-to-normal vision.

Apparatus

Participants stood on an elevated walkway (4.90 m long × 0.98 m wide × 0.64 m high). Two walls defined the horizontal extent of the opening: a stationary wall (1.22 m wide × 1.92 m high) attached to one side of the walkway and a moveable wall (0.92 m wide × 1.92 m high) perpendicular to the walkway. For horizontal openings, an experimenter adjusted the width of the opening from 30 to 90 cm in 0.5 cm increments by sliding the moveable wall toward or away from the stationary wall (Fig. 1a). For vertical openings, a vinyl screen fit into a wooden frame above the stationary and moveable walls with the horizontal opening set at 90 cm; an experimenter adjusted the height of the screen from 130 to 190 cm in 0.5 cm increments by pulling a hidden cord (Fig. 1b). A curtain at the end of the walkway prevented participants from using landmarks in the room to judge opening size.

Three video cameras recorded the session. Overhead and side camera views captured participants' movements as they walked through the openings. A measurement camera recorded calibration markings to allow precise adjustment of the apparatus. The three camera views were combined in a single digital video file for later coding.

Procedure

Participants stood barefoot at the end of the walkway and judged whether gait modifications would be necessary to pass through various openings. Then they walked through openings of different sizes. Judgment trials preceded walking trials to prevent participants from learning from the experience of walking through openings of different sizes (Franchak et al. 2010). For judgment and walking conditions, we blocked horizontal and vertical trials and counterbalanced the order across participants. At the start of each trial, participants stood 2.5 m (approximately 5–6 steps) from the opening. They turned away from the opening until the experimenter set the apparatus to the correct width or height and cued them to turn around.

For every trial, participants answered the question, "Can I walk straight through the opening?" On horizontal judgment trials, participants said "yes" if they thought they could walk straight through the opening and "no" if they thought they would need to turn to avoid touching the sides of the apparatus. On vertical judgment trials, participants said "yes" if they thought they could walk straight through the opening and "no" if they thought they would need to duck their heads or bend their knees to avoid touching the screen.

During walking trials, participants walked through openings of varying width in the horizontal condition and of varying height in the vertical condition. Experimenters instructed participants to walk through each opening and to turn or duck as necessary to avoid touching the sides or top

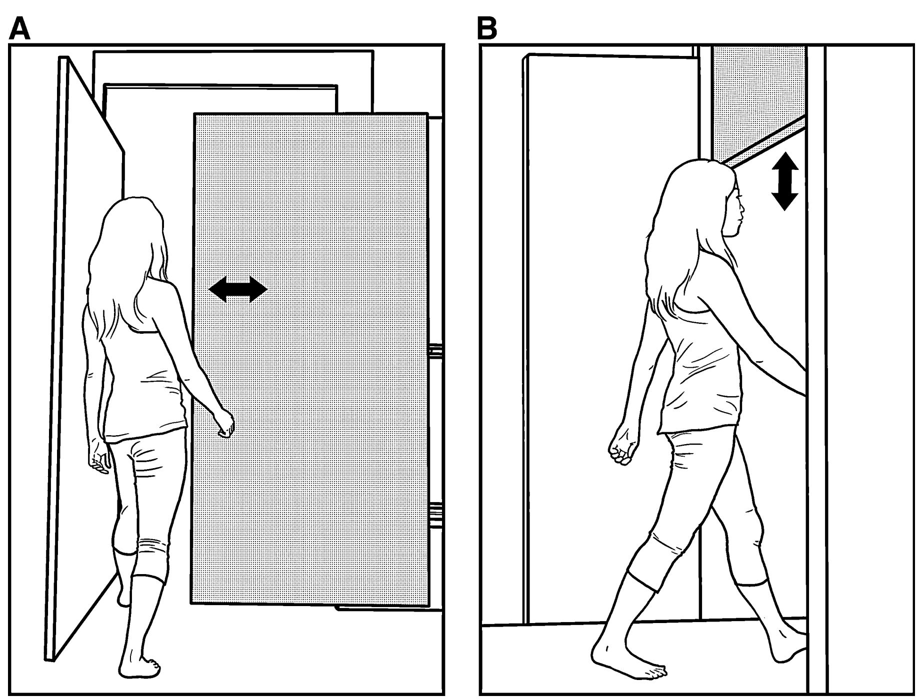

Fig. 1 Adjustable opening apparatus presented horizontal and vertical openings that elicit gait modifications: **a** Horizontal openings were adjusted by moving a sliding wall, and **b** vertical openings were adjusted by moving a screen. *Arrows* indicate the direction of the adjustment for each condition

of the opening. An experimenter notified participants that the wooden walls were solid and the screen contained a sturdy bar, so they should avoid collision. Before the horizontal walking trials, an experimenter marked the tops of participants' shoulders with colored tape so the alignment and position of their shoulders would be clearly visible in the overhead camera view.

To determine each participant's threshold for each condition, we analyzed the proportion of trials without need for gait modification as a function of opening size. For verbal judgments, we calculated the proportion of "yes" responses for each opening size. For gait modifications, we calculated the proportion of trials in which the participant walked straight through at each opening size. We calculated verbal judgment and gait modification functions by fitting cumulative normal distributions to each set of responses using maximum likelihood estimation for the mu and sigma parameters (Berger 1985). We used the mu parameters of each function as the judgment threshold—the opening size corresponding to "yes" responses on 50 % of trials—and the gait modification threshold—the opening size corresponding to walking straight through the opening on 50 % of trials. Sigma parameters from each function provided measures of response variability across trials for each participant in each condition.

A customized MATLAB program suggested opening sizes based on an adaptive psychophysical protocol to determine the threshold for each participant in each block of trials (for details, see Franchak et al. 2010). The procedure began with 4–6 binary search trials to find an approximate threshold: The experimenter presented the maximum and minimum opening sizes and determined successive opening sizes from the midpoint of the participant's smallest "yes" response and largest "no" response. The experimenter then presented 15–25 probe trials at random opening sizes within three standard deviations of the estimated threshold.

After the judgment and walking tasks, the experimenter measured participants' standing height and shoulder width. To measure shoulder width, the participant stood in the opening with the left shoulder touching the stationary wall, and an experimenter adjusted the moving wall until it touched the participant's right shoulder and recorded the corresponding opening width. The experimenter measured standing height using a wall-mounted stadiometer with the participant's head in the Frankfort position.

Data coding

For verbal judgments, an experimenter recorded participants' responses online. For the walking conditions, one primary coder and one reliability coder determined gait modifications from video using OpenSHAPA software (www.openshapa.org). As in previous research (Warren and Whang 1987; Higuchi et al. 2011), gait modifications were coded if participants' shoulders or heads deviated from their baseline positions during normal walking. In the horizontal condition, the experimenter coded trials as gait modifications if participants' shoulders rotated 20° or more from parallel as they walked through the opening (pilot coding revealed that 20° was the smallest turn that could be coded reliably); if not, they coded trials as walking straight through. To determine shoulder rotation, coders compared the alignment of participants' shoulders to a semitransparent graphic of a 20° angle positioned over the video. In the vertical condition, the experimenter coded trials as modifications if participants lowered their heads beyond the dips caused by normal walking; otherwise, they coded trials as walking straight through. A semitransparent horizontal line was set to the lowest position of the participants' head during normal walking as they approached the opening; this visual reference allowed us to objectively determine ducking if the top of the head dipped below the line. The experimenter also scored whether the participant erred by touching the sides or top of the opening. A reliability coder did the same for 25 % of each participant's trials, and experimenters resolved disagreements by discussion. Inter-rater reliability was 95.1 % for the horizontal condition and 93.2 % for the vertical condition. After coding, we recalculated gait modification functions using the behaviors coded from video and used the resulting threshold and variability measures in subsequent analyses.

Results

Although participants' task was to modify their gait to avoid touching the sides or top of the opening, 15 participants bumped their shoulders in the horizontal condition and 15 (not necessarily the same participants) bumped their heads in the vertical condition. However, touches were infrequent, occurring on an average of 4.8 % ($SD = 5.0$) of trials in the horizontal condition and 4.8 % ($SD = 5.1$) of trials in the vertical condition. These "bump" trials were excluded from further analyses so that thresholds would reflect which openings participants were able to navigate without error. However, we found the same pattern of results with error trials included.

Preliminary analyses showed no effects of condition order on verbal judgments or gait modifications. Thus, we analyzed the data without regard to condition order.

Thresholds scaled to body dimensions

Shoulder width and standing height approximate the smallest opening sizes at which a participant could walk straight through without turning or ducking, respectively. Shoulder width ranged from 38.7 to 55.1 cm ($M =$ 46.1 cm), and height ranged from 151.5 to 186.4 cm ($M = 169.3$ cm). As shown in the top row of Fig. 2, shoulder width was correlated with horizontal judgment thresholds ($r = .49$, $p = .016$) and gait modification thresholds ($r = .80$, $p < .001$), indicating that participants scaled both decisions and actions to relevant body dimensions. Thresholds scaled more strongly in the vertical conditions: As shown in the bottom row of Fig. 2, standing height was correlated with vertical judgment thresholds ($r = .90$, $p < .001$) and gait modification thresholds ($r = .99$, $p < .001$).

Turning and ducking ratios and buffers

To account for the range in body size and to allow comparison of horizontal and vertical conditions, we scaled participants' thresholds to their body dimensions in two ways. As in prior research, we calculated *turning ratios* and *ducking ratios* for gait modifications by dividing thresholds in the horizontal conditions by shoulder width and dividing thresholds in the vertical conditions by height. *Judged turning ratios* and *judged ducking ratios* were calculated by dividing judgment thresholds by the relevant body dimension. Thus, turning and ducking ratios represent affordances for passage in body-relative terms.

We also calculated *turning buffers* and *ducking buffers* for gait modifications by subtracting shoulder width from horizontal gait modification thresholds and subtracting height from vertical gait modification thresholds. This value reveals participants' smallest buffer in centimeters for walking straight through—with less space available, participants would transition to turning or ducking. Finally, we calculated *judged turning buffers* and *judged ducking buffers* by subtracting shoulder width from horizontal judgment thresholds and height from vertical judgment thresholds. Buffers represent the absolute space requirements for each opening and are not scaled to body size.

In the horizontal condition, turning ratios averaged 1.10 ($SD = 0.07$) times participants' shoulder widths, resulting in a mean turning buffer of 4.5 cm ($SD = 2.8$). Participants' judged turning ratios matched their actual turning ratios ($M = 1.09$, $SD = 0.12$), with judged turning buffers averaging 3.9 cm ($SD = 5.4$) of space needed to walk straight through.

In the vertical condition, thresholds matched participants' heights more closely. Mean ducking ratios were 1.00

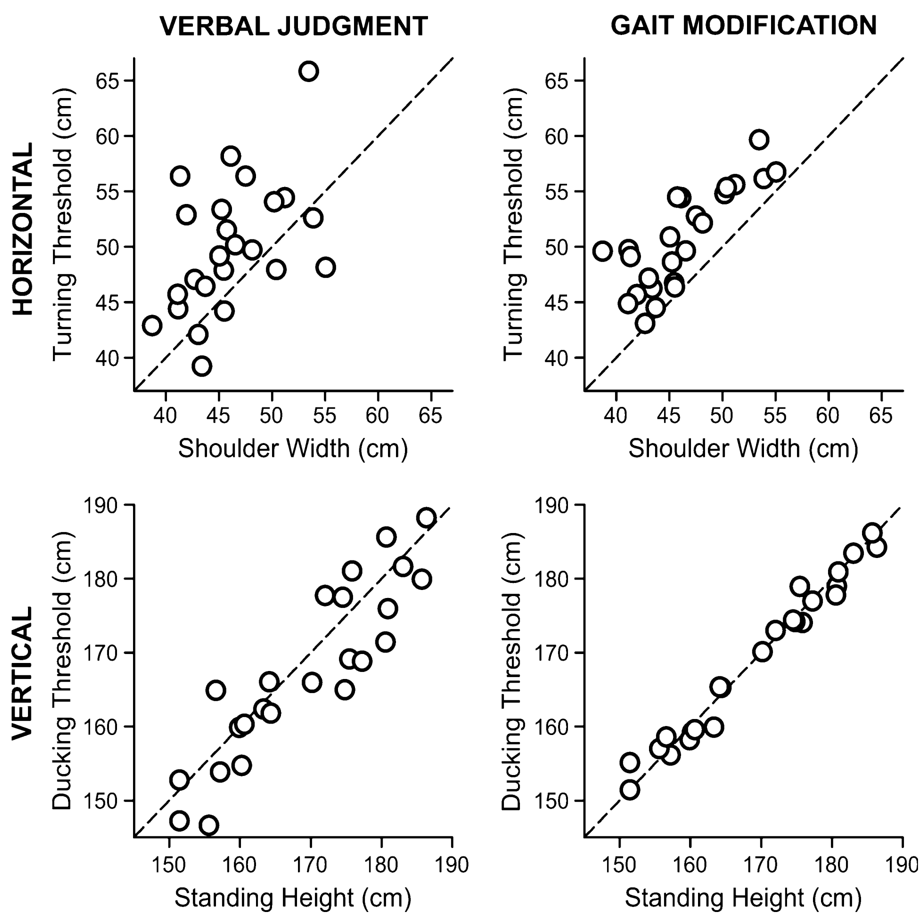

Fig. 2 Scatter plots showing correlations between thresholds and relevant body dimensions in the verbal judgment and walking tasks. *Top row*: shoulder width scaling of judged turning thresholds (*left*) and actual turning thresholds (*right*). *Bottom row*: height scaling of judged ducking thresholds (*left*) and actual ducking thresholds (*right*)

($SD = 0.01$) times participants' heights. On average, ducking buffers were -0.12 cm ($SD = 1.8$), indicating that the average participant only ducked for barriers that were slightly *below* the top of the head. Likewise, participants judged that they would duck at ratios of 0.99 ($SD = 0.03$) with judged ducking buffers of -1.8 cm ($SD = 5.1$), that is, reporting that they would only duck when barriers were more than 1.8 cm below standing height.

As shown in Fig. 3a and b, both turning ratios and turning buffers were greater than ducking ratios and ducking buffers, but judged ratios and buffers did not significantly differ from the actual gait modification values. A 2 (opening type: horizontal, vertical) × 2 (task: verbal judgment, gait modification) repeated measures ANOVA on ratios confirmed a main effect of opening type, $F(1, 23) = 39.55$, $p < .001$, partial $\eta^2 = .63$, but not of task, $F(1, 23) = 0.80$, $p = .38$, partial $\eta^2 = .03$. Similarly, a 2 (opening type) × 2 (task) repeated measures ANOVA on buffers also revealed a main effect of opening type, $F(1, 23) = 43.08$, $p < .001$, partial $\eta^2 = .65$, but not of task, $F(1, 23) = 1.88$, $p = .183$, partial $\eta^2 = .08$. The difference between verbal judgments and gait modifications was similar for both opening types: There was no interaction between opening type and task for ratios, $F(1, 23) = 0.004$, $p = .951$, partial $\eta^2 < .01$, or buffers, $F(1, 23) = 0.81$, $p = .378$, partial $\eta^2 = .03$.

Variability

The sigma parameters of the functions fit to participants' data for each condition indicated the variability of responses for each individual. As shown in Fig. 3c, both verbal judgments and gait modifications were more variable for horizontal openings than for vertical openings. For verbal judgments, the average sigma was 1.34 cm ($SD = 1.00$) in the horizontal condition and 0.97 cm ($SD = 0.84$) in the vertical condition. For gait modifications, the average sigma was 1.45 cm ($SD = 1.48$) in the horizontal condition and 0.54 cm ($SD = 0.44$) in the vertical condition. A 2 (opening type) × 2 (task) repeated measures ANOVA confirmed a main effect of opening type, $F(1, 23) = 13.97$, $p = .001$, partial $\eta^2 = .38$, but variability did not differ for task, $F(1, 23) = 0.749$, $p = .396$, partial $\eta^2 = .03$. The difference in horizontal and vertical variability was similar across tasks: The ANOVA did not reveal an interaction, $F(1, 23) = 1.89$, $p = .182$, partial $\eta^2 = .08$.

Correspondence between verbal judgments and gait modifications

To directly assess the correspondence between verbal judgments and gait modifications, we calculated a measure of *judgment error* by finding the absolute value of the difference between verbal judgment thresholds and gait modification thresholds for each participant in each condition. The average judgment error was 4.0 cm ($SD = 2.5$) in the horizontal condition and 4.8 cm ($SD = 2.8$) in the vertical condition. Judgment error did not differ significantly between the two opening types, $t(23) = -1.02$, $p = .317$.

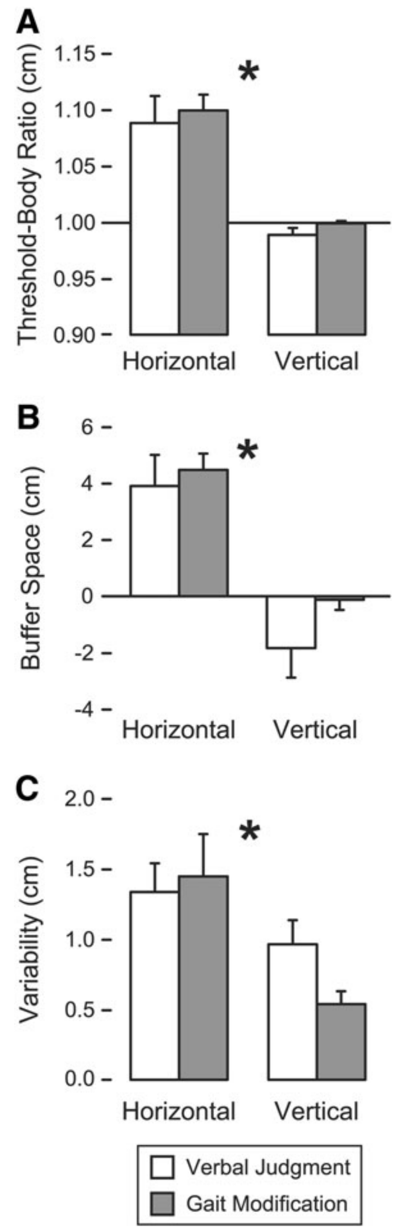

Fig. 3 Means and standard errors of **a** turning and ducking ratios, **b** turning and ducking buffers, and **c** response variability. *Gray bars* indicate values for actual gait modifications, and *white bars* show verbal judgments. Ratios greater than 1 and buffers greater than 0 (*horizontal reference lines*) indicate that participants left space in addition to their shoulder width and height

Although judgment errors were relatively small, the possibility remains that a few centimeters of error were the result of participants making judgments based on static body dimensions rather than actual gait modifications. We employed hierarchical linear regression to determine whether participants' judgments were more strongly predicted by body dimensions or actual gait modification thresholds in each condition.

For horizontal openings, we tested models that predicted participants' judged turning thresholds for turning based on shoulder width and actual turning thresholds. In the first model, we first entered shoulder width and found that it accounted for 23.8 % of variance in judged turning thresholds, $F(1,\ 22) = 6.877$, $p = .016$. Entering actual turning thresholds into the model accounted for an additional 14.5 % of variance (R^2 change $p = .037$). In a second model, we entered turning thresholds first and found that they accounted for 36.8 % of variance in judgments, $F(1, 22) = 12.816, p = .001$. Adding shoulder width to the model explained only 1.5 % of additional variance (R^2 change $p = .95$), suggesting that participants' judgments are explained by actual gait modifications, not static body dimensions.

A similar analysis is not feasible in the vertical condition because of multicollinearity between ducking thresholds, judged ducking thresholds, and standing height (bottom row of Fig. 2). Because height almost perfectly predicted actual gait modifications for ducking, we cannot separate the unique contributions to participants' judged ducking thresholds.

Discussion

The current study demonstrated that walkers allow for more space when turning to fit through narrow openings than when ducking under an overhead barrier, in terms of both absolute and body-relative measurements. Verbal judgments of whether gait modifications were necessary for passage through openings closely matched actual thresholds for both turning and ducking. For horizontal openings, actual affordances for navigating horizontal openings accounted for participants' verbal judgments, not static measurements of shoulder width. Finally, we found that both verbal judgments and gait modifications are more variable for horizontal compared to vertical openings.

Tuning gait modifications to body size and motion

In the current study, walkers turned to pass through openings 1.1 times their shoulder width but only ducked to pass under barriers right at their actual height. Previously reported turning ratios have likewise been larger than reported ducking ratios (Warren and Whang 1987; van der Meer 1997; Higuchi et al. 2006; Stefanucci and Geuss 2010). Our ratios are smaller than those found in the literature, but the trend of turning ratios exceeding ducking ratios is the same. The fine resolution (0.5 cm precision) of our apparatus is likely the reason for thresholds being closer to body dimensions: We were able to pinpoint thresholds by presenting trials within a narrow range around participants' body dimensions. Previous studies may have been limited by testing fewer opening sizes with larger increments between opening sizes, ranging from 2.5 to 13 cm (Warren and Whang 1987; van der Meer 1997; Wagman and Malek 2008; Stefanucci and Geuss 2010). Variations in instructions to participants might also account for differences in ratios. For example, Warren and Whang (1987) instructed participants to turn "if they wished," which could have led to more conservative response criteria than our instructions to turn as needed to avoid touching the opening.

The range of turning and ducking ratios in the literature demonstrated the need for a within-subjects comparison to establish differences in gait modifications for horizontal and vertical openings. The current study confirms that walkers allow for comparatively more space for horizontal openings—an additional 10 % beyond static body dimensions—likely due to differences in the body's movements. For instance, when passing through horizontal openings, walkers must ensure clearance on both sides of their shoulders, but when passing under a barrier, they need only one clearance area above their heads. Kinematic differences in lateral sway and vertical bounce likely play a role in spatial requirements. Lateral sway moves the trunk from side to side, whereas vertical bounce only makes the body shorter (Murray et al. 1964). This vertical oscillation could allow walkers to pass through openings at and just below their heights without modifying their gait, which is one explanation for why participants' ducking thresholds were an average of 0.1 cm *below* their standing heights. That some participants could manage barriers slightly below their standing height challenges the notion of static height as the key metric for the affordance of overhead clearance—dynamic walking height appears to be of greater relevance.

If a larger buffer reflected a conservative bias to avoid injury, we would expect walkers to leave greater buffers for vertical openings due to the relatively greater penalty of bumping their heads. However, we found the opposite pattern. Moreover, participants erred by touching the opening at the same rate in both conditions ($M = 4.8$ % of horizontal and vertical trials), indicating that participants were no more cautious in one condition than in the other. In previous work, judgments of turning for openings greater than one's shoulder width were interpreted as error in perceiving opening size (Wraga 1999) or cautious avoidance of collision (Warren and Whang 1987). Our evidence suggests something different. By tuning gait modifications to body dimensions with a greater ratio for horizontal than vertical openings, participants accurately accounted for the demands for gait modifications in each dimension. The buffer does not indicate caution or error. It indicates sensitivity to the spatial requirements of walking. Most likely, actors combine information about the probability of success with information about penalties for error to make motor decisions—a *cost function* in decision theory integrates probability and penalty (Glimcher 2003). Assessing risk takes probability information into account, but we do not find evidence that perceived possibilities for action are inherently biased by penalties for error.

Furthermore, the current study showed that gait modifications for horizontal openings are more variable than for vertical openings, which might also lead walkers to leave more space while walking through. In contrast, the relative precision of gait modifications in the vertical condition may have allowed participants to match their gait modifications for vertical openings more closely to their heights. Previous research showed that participants optimally account for the variability of their hitting accuracy by aiming for the furthest edge of a target area, away from a penalty area (Trommershäuser et al. 2008). For horizontal openings, walkers may leave larger buffers to account for greater variability in their gait modifications so as to avoid collision.

Variability from trial to trial might depend on variability in the movements themselves. One possibility is that lateral sway might be more variable from step to step than vertical bounce, increasing the buffer that walkers leave for passage through horizontal openings. In addition, it is possible that coding behaviors from video failed to capture more subtle modifications. We categorized turning, ducking, and walking straight through into discrete states. In future studies, the use of motion tracking would provide more detail about the degree of modification and the amplitude and variability of lateral sway and vertical bounce during the approach to the opening. Motion tracking data may help discern whether movement amplitude, movement variability, or both amplitude and variability account for larger buffers in the horizontal condition.

Accuracy and consistency of verbal judgments

Participants' verbal judgment thresholds closely matched gait modification thresholds in both conditions. Previous studies have reported similar ratios for vertical verbal judgment thresholds to our findings for both verbal judgments and gait modifications (Wagman and Malek 2008; Wagman and Malek 2009; Stefanucci and Geuss 2010). Agreement between verbal judgments and gait modifications for horizontal openings is consistent with Warren and Whang's (1987) finding that verbal judgments made while participants were stationary were the same as judgments made while walking toward the opening.

Verbal judgments were close to gait modifications in terms of the absolute difference between thresholds and the scaling of thresholds to body dimensions. Participants were quite accurate in determining whether passage through openings required gait modifications while standing at a distance, only erring by about 4.4 cm across conditions. This is consistent with observers' accuracy in judging their ability to squeeze through openings: Franchak and colleagues (2010) reported a mean absolute difference of 3.1 cm between prior judgments and thresholds for fitting sideways through horizontal openings. In that task, affordances for squeezing through openings also depend on dynamic body size—how much the body can compress when squeezing through—not on the sideways dimensions of the body at rest (Comalli et al. in prep).

The current study challenges the idea that affordances for passage can be specified by simple geometric relations between static body dimensions and opening size. The division of affordances into body-scaled and action-scaled may be a false dichotomy: The classic example of a body-scaled affordance, walking through openings, is in fact action-scaled. In the horizontal condition where gait modification thresholds differed from body dimensions, participant's turning judgments were best predicted by the actual spatial requirements for turning, not shoulder width. However, abandoning geometric body scale might also imply that eye height information alone is not sufficient for accurately perceiving whether gait modifications are necessary. Instead, as Fath and Fajen have suggested (2011), observers might detect affordances for passage based on optically specified head-sway and step-length information, both of which are available while walking. Indeed, there is an ongoing debate about whether being in motion facilitates perception of affordances for some actions, such as catching a fly ball (Oudejans et al. 1996; cf. Fajen et al. 2011).

Regardless, accuracy of prior judgments demonstrates that people are sensitive to the spatial requirements of the moving body even while stationary, to the extent that they can detect specific possibilities for action and demands for adaptation. Head-sway and step-length might not help during stationary judgments. One possibility is that walkers learn about how the body moves during certain actions from experience. We have found that 20 trials of experience squeezing through apertures improve judgment accuracy (Franchak et al. 2010). Certainly, walkers have ample opportunity to learn from experience, even during infancy (Adolph et al. in press). Another possibility is that other information sources are available while stationary, such as the optical information generated through postural sway (Yu et al. 2011).

Conclusion

Theories of perception often attempt to distinguish whether observers perceive the environment in absolute or body-relative terms (Mark 1987; Warren 1984). The current study extends the idea of a body-relative view to suggest that we perceive the world with a body metric that includes the size of the body as it moves. Even while stationary, walkers considered the dynamic properties of walking that influence spatial requirements differently in horizontal and vertical directions. A challenge for future research will be identifying information sources that enable walkers to perceive the world in terms of the body in motion. Viewing the world with a dynamic body metric would allow people to flexibly adapt to changes in the kinematics of walking and thereby detect affordances for guiding action accurately.

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