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Dynamic perception of dynamic affordances: walking on a ship at sea

Hannah Walter, Jeffrey B. Wagman, Nick Stergiou, Nurtekin Erkmen & Thomas A. Stoffregen

Keywords

Gait, Posture, Affordance, Motor control, Biomechanics

Abstract

Motion of the surface of the sea (waves, and swell) causes oscillatory motion of ships at sea. Generally, ships are longer than they are wide. One consequence of this structural difference is that oscillatory ship motion typically will be greater in roll (i.e., the ship rolling from side to side) than in pitch (i.e., the bow and stern rising and falling). For persons on ships at sea, affordances for walking on the open deck should be differentially influenced by ship motion in roll and pitch. Specifically, the minimum width of a walkable path should be greater when walking along the ship's short, or athwart axis than when walking along its long, or fore-aft axis. On a ship at sea, we evaluated the effects of walking in different directions (fore-aft vs. athwart) on actual walking performance. We did this by laying out narrow paths on the deck and asking participants (experienced maritime crewmembers) to walk as far as they could while remaining within the lateral path boundaries. As predicted, participants walked farther along the athwart path than along the fore-aft path. Before actual walking, we evaluated participants' judgments of their walking ability in the fore-aft and athwart directions. These judgments mirrored the observed differences in walking performance, and the accuracy of judgments did not differ between the two directions. We conclude that experienced maritime crewmembers were sensitive to affordances for walking in which the relevant properties of the environment were exclusively dynamic.

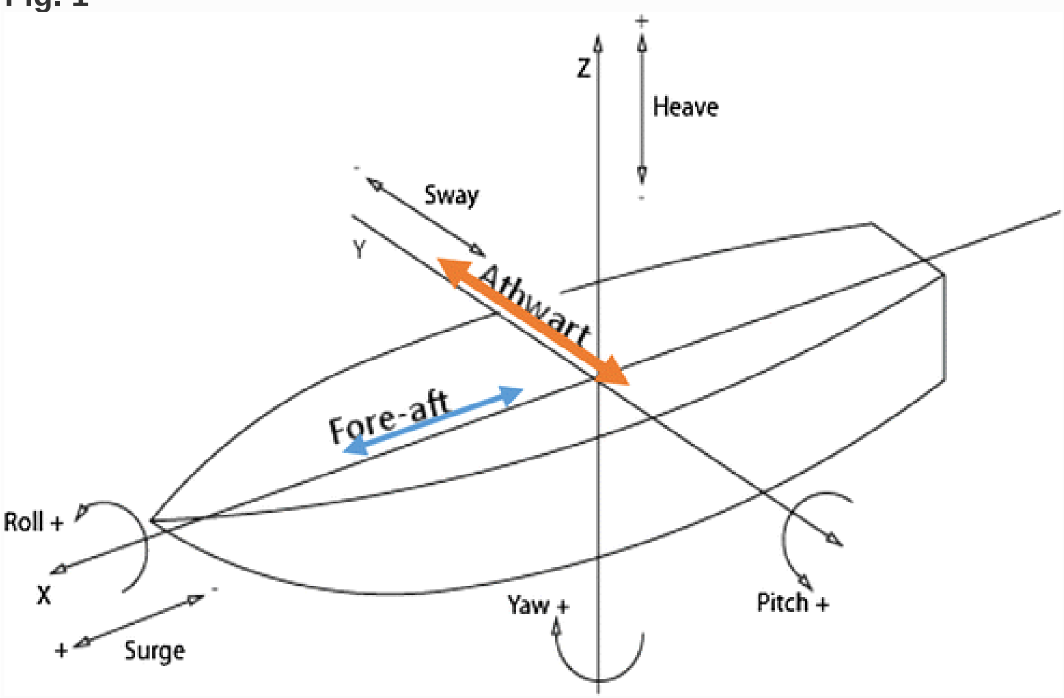
Introduction

Affordances are behaviors that are available to a given organism (or group of organisms) in a given environment (Gibson 1979/1986). Affordances emerge from relations between properties of the organism (or organisms) and properties of the environment (Stoffregen 2003). Affordances are based upon dynamic action capabilities. One example is running to catch a fly ball (Oudejans et al. 1992), which is dependent upon the ratio of time available (before the ball hits the ground) and time required for the perceiver/actor to arrive at the impact point. Another example is crossing the street in traffic (Lee et al. 1984; Plumert et al. 2004), which is dependent upon the ratio of time available (between successive cars) and the time needed to cross.

One common human behavior is locomotion, such as walking, running, or rolling in a wheelchair. Opportunities for locomotion emerge from relations between properties of the environment and properties of the person. Many studies have examined the opportunity to walk, run, or roll through apertures. Passage through an aperture is afforded when the width and height of the aperture are greater than the (static or dynamic) width and height of the person, and experimental participants are able to differentiate apertures that afford passage from those that do not (e.g., Franchak et al. 2012; Higuchi et al. 2004, 2011; Yu et al. 2011). Similarly, locomotion is afforded when the ground surface is rigid, that is, when it resists the forces that are applied by the walker (or crawler). Infants can differentiate surfaces that are sufficiently rigid to support locomotion from those that are not (e.g., Gibson et al. 1987; cf. Berger et al. 2005).

We evaluated the perception of an affordance for walking that was influenced by motion of a ship at sea. Ocean swells and waves give rise to oscillatory ship motion in six degrees of freedom (DOF); three of rotation (roll, pitch, and yaw), and three of translation (surge, sway, and heave); (Fig. 1). Ship motion typically is concentrated below 0.2 Hz (e.g., Stoffregen et al. 2009). This highly complex motion contrasts with motion within a single DOF, which characterizes many laboratory research devices, including treadmills, moving platform posturography (e.g., Nashner and McCollum 1985), and many whole-body motion devices that move seated participants either vertically (O'Hanlon and McCauley 1974) or horizontally (Nawayseh and Griffin 2005). Some whole-body motion devices feature six DOF motion, but such devices typically are not large enough to suit the requirements of our study. For example, Dobie et al. (2003) evaluated walking on a six DOF ship simulator, but the maximum walkable straight line path was 3 m.

Fig. 1



Ship motion occurs in six degrees of freedom. Angular ship motion comprises roll, pitch, and yaw, while translator ship motion comprises surge, sway, and heave. The figure also indicates the ship's fore-aft and athwart axes

The main purpose of walking is to move forward, but walking necessarily includes lateral oscillations of the body as weight shifts between the feet. In the present study, we identified an affordance that was influenced by relations between a dynamic property of the participant (the ability to modulate lateral oscillations in walking) and a dynamic property of the surface of support (angular motion of a ship at sea). Motion of the ground surface can influence walking. Common examples include walking the length of subway or train cars, and stepping onto or off of a moving walkway (of the kind commonly found in large airports), which often causes momentary but very noticeable changes in gait. This example is convenient because many readers will be familiar with it from personal experience. However, it is of limited relevance to the present study, in part because moving platforms typically are limited in the DOF of movement, as compared with ships, where gait is constrained by the complex, six DOF motion of ships at sea.

Ship motion induces global changes in gait that are sufficiently general that they can be seen by casual observers; sailors have a “rolling gait” that persists for several hours after return to land (Stevens and Parsons 2002). Given these effects, controlled variations in motion of the ground surface might be used to address the perception of how walking affordances can be influenced by surface motion. Yet, generally the experimenter cannot exercise control over ship motion. Conveniently, regular variations in ship motion occur naturally, as a consequence of naval architecture. Generally, ships are longer than they are wide, and for this reason angular ship motion will tend to be greater in roll than in pitch. Ship motion in roll occurs around the ship’s fore-aft axis, while ship motion in pitch occurs around the ship’s athwart axis (Fig. 1). At sea, the kinematics of upright stance are powerfully affected by facing fore-aft versus athwart (Chen and Stoffregen 2012; Munafo et al. 2015; Varlet et al. 2014, 2015). In addition, in walking on a ship at sea the timing of footfalls differs between walking along the ship’s fore-aft versus athwart axes (Haaland et al. 2015). In the present study, we asked whether the fore-aft/athwart distinction would alter the distance that mariners could walk along a narrow path (i.e., the affordance for maintaining dynamic gait within a narrow path), and whether experienced mariners would be sensitive to these differences in a prospective manner. That is, we asked whether experienced mariners would be sensitive to direction-specific affordances for locomotion.

When at rest (e.g., at the dock), the surface of the deck was the same in all directions. At sea, the static properties of the deck were unchanged, including its material substance, the way it reflected light, and its topography, or geographical layout. Yet at sea the deck was in motion, and this motion varied as a function of direction. Ship motion created a “force topography”, or a dynamic topography. The way that the deck moved varied as a function of direction. Angular ship motion tends to influence gait as a function of direction. When walking athwartship (i.e., from port to starboard, and vice versa), ship motion in pitch tends to affect side-to-side oscillation of the body. When walking fore-aft (i.e., toward the bow, or stern), lateral oscillation tends to be affected by ship motion in roll. Because ship motion typically is greater in roll than in pitch, lateral oscillation at sea tends to be greater (and more variable) when walking fore-aft than when walking athwartship. Therefore, when asked to walk along a narrow path at sea, we predicted that performance would be better when walking athwart than when walking fore-aft. We also predicted that experienced mariners would be sensitive to the differential effects of roll and pitch on gait, in general, and on lateral oscillation during gait, in particular. To test each of these predictions, we created narrow pathways on the open deck of a ship at sea. One pathway was parallel to the ship's long, or fore-aft axis, and the other was parallel to the ship's short, or athwart axis (see Figs. 1, 3). We expected that participants would be able to walk farther along the athwart path. Before assessing walking performance, however, we asked participants to judge how far they would be able to walk along each path. We expected these judgments to differ as a function of path direction (fore-aft vs. athwart), and we expected the difference in judgments to mirror the difference in actual walking performance.

In the laboratory, devices that permit the control of whole-body motion in multiple axes rarely are large enough to permit walking (for a rare example, see Dobie et al. 2003). By contrast, unfettered walking is common on ships at sea. We could not control the motion of the ship, but we were able to manipulate existing motion as an independent variable in our study.

Method

Participants

Our sample comprised 13 men and three women, ranging in age from 20 to 72 years (mean = 45.6 years), in height from 1.5 to 1.9 m (mean = 1.78 m) and in weight from 68 to 172 kg (mean = 88 kg), and with 2–38 years (mean = 18.5 years) experience working at sea. As part of the consent process, participants indicated that they suffered from no history of balance disorders, vestibular dysfunction, seizures, or dizziness. The experimental protocol was approved in advance by the University of Minnesota IRB.

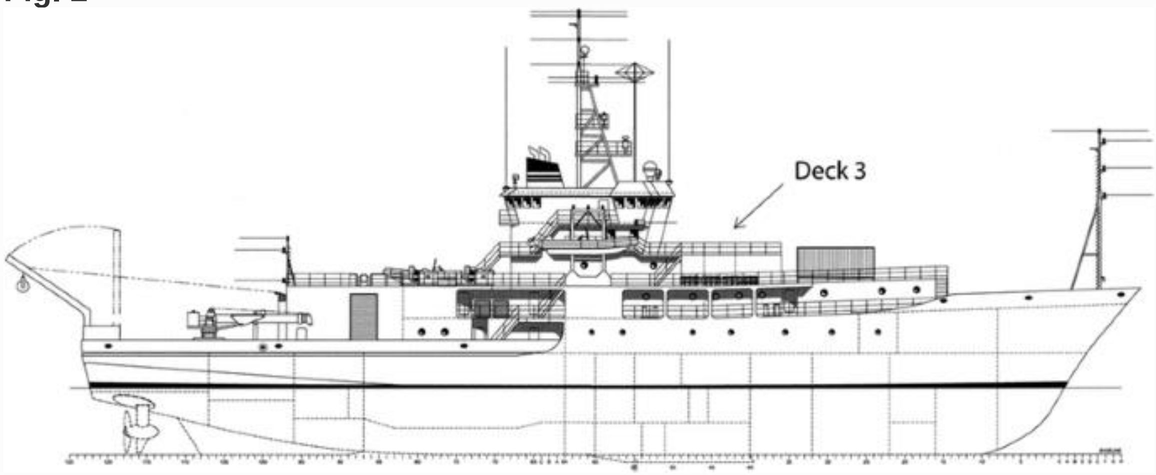
Setting

Testing was conducted on the R/V Thomas G. Thompson (Fig. 2) during a transit from Seattle, Washington to San Diego, California. The ship was 84 m long with a 16 m beam. It displaced 3500 tons and cruised at 12 knots.

Procedure

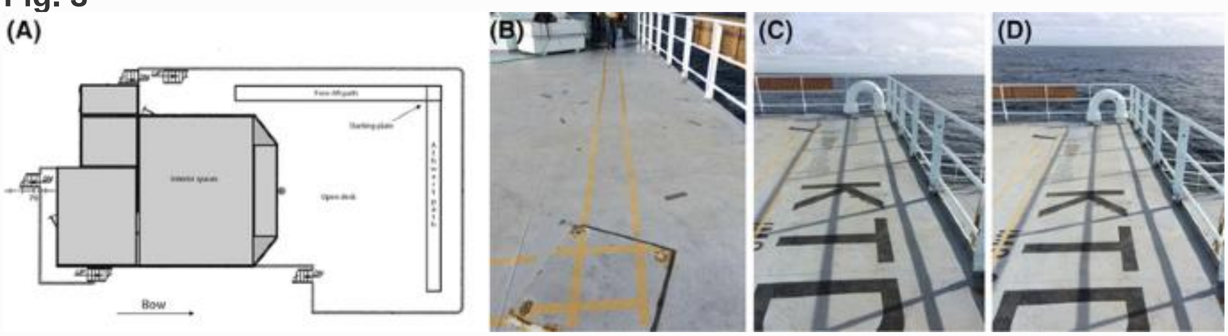
The ship departed Seattle on January 10 2016 and arrived in San Diego on January 15. The data were collected on January 14, that is, on the fifth day of the voyage. Testing was conducted on the third deck of the ship, which was free from clutter (Figs. 2, 3). Two pathways were created using clearly visible tape and were laid out on the long (fore-aft) and short (athwart) axes (Figs. 3, 4). At the intersection of the two pathways was a starting plate, where participants stood with their feet on the taped lines. The purpose was to standardize foot position to reduce variation in the walking distance. Each path was 8.9 m long by 0.3 m wide. The length was the maximum that was available on the deck. The width was selected from informal testing so as to provide a moderate challenge given the ship motion on the day the experiment was conducted.

Fig. 2



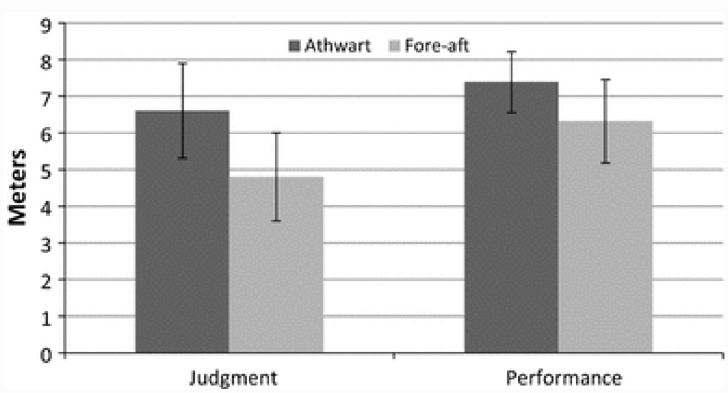
The R/V Thomas G. Thompson. The *arrow* indicates the portion of Deck 3 on which the study was carried out

Fig. 3



a Overhead view of Deck 3, illustrating the placement of the walking paths. **b** Experimental setting, showing the starting plate, at the *bottom* of the photograph, and the fore-aft path. At *lower left*, the beginning of the athwart path is visible. **c**, **d** Roll motion on the day of testing. The camera is facing the port side; the bow is to the *right*. A portion of the athwart walking path is visible, ending at the starting plate. In **c**, the ship has rolled to starboard (the distant railing is elevated almost to the horizon), while in **d** the ship has rolled to port (the distant railing is well below the horizon)

Fig. 4



Statistically significant effects of direction (athwart vs. fore-aft) on mean judgments of walkable distance, and on walking performance (mean distance actually walked). The *error bars* illustrate the 95% confidence interval of the mean

Familiarization phase

Participants wore shoes in compliance with the ship regulations. Beginning on the marked starting plate, participants were asked to walk comfortably along the marked paths while ignoring the lines. “Keep your eyes on the end line (or plate), ignore the parallel lines, and walk comfortably to the end line (or plate)”. Participants were required to walk out from the starting plate and back to the starting plate twice in the fore-aft and athwart directions. The purpose of the familiarization phase was *not* to provide practice at walking in different directions, which (presumably) participants had learned in their general experience, and in the preceding days of the voyage. Rather, the purpose was to provide practice at the traversing the marked paths that we had created for the study.

Judgment task

After familiarization, participants stood on the starting plate and were asked to estimate how far they could walk along each path without stepping on or over the lines. For each judgment trial, the participant was asked to look at the designated path and estimate “how far do you think you could walk along this path without stepping on or over the lines?”. To indicate the participant’s judgment, an experimenter stood near the participant, facing toward them while holding a marker (a 0.25 m length of a wooden 4 × 4). After a ready signal, the experimenter slowly walked backward along the path, and the participant indicated where the experimenter should place the marker to indicate their judgment. Each participant gave two judgments for each path, for a total of four judgments. Across trials, judgments alternated between paths, with odd-number participants beginning with the fore-aft path, and even-numbered participants beginning with the athwart path.

Performance (walking) task

After completing the judgment task, participants were asked to walk each of the paths. “Please do not look at your feet. Keep your eyes on the end line (or plate) and walk so as to avoid stepping on the lines.” Each participant completed a total of 12 trials, comprising three laps (out and back) along each path (originating from the starting plate), with each length constituting one performance trial. If the participant stepped on or over the lines, it was classified as a “fault” and the performance length was recorded from this spot. Each of three experimenters watched for faults, with one experimenter on each side of the participant (following along) and one experimenter remained at the starting plate.

Data analysis

For judgments, we took the mean of the two judgments of the fore-aft path, and the mean of the two judgments in the athwart path. For performance trials, we took the mean of the six trials for the fore-aft path, and for the athwart path. Thus, for each participant we took four numbers (mean judgment fore-aft, mean judgment athwart, mean performance fore-aft, and mean performance athwart). We conducted inferential statistics on the means across participants. Using paired sample t tests, we compared judgments in the fore-aft versus athwart paths, and we compared performance in the fore-aft versus athwart paths. To evaluate the accuracy of judgments, we expressed judgments as a proportion of actual walking ability (judgment mean/performance mean) and compared these proportions for the fore-aft versus athwart paths.

Results

Data were collected on the 5th day of the transit, between 12:00 and 17:00. During data collection, the sea state was 3 on the Beaufort Scale (Beer 1997), which corresponds to relatively mild ship motion (cf. Chen and Stoffregen 2012; Stoffregen et al. 2013, 2009). Roll motion during data collection is illustrated in Fig. 3.

Anecdotally, there were more visible adjustments to posture and gait while walking the fore-aft path than while walking the athwart path. That is, participants more often disobeyed instructions (to walk comfortably) while walking fore-aft, making visible efforts to stay within the designated path. These anecdotal observations are consistent with the data, suggesting that keeping the feet inside the path lines was more challenging along the fore-aft path than along the athwart path.

The results are summarized in Fig. 4. Judgments differed between path directions: participants judged they could walk further along the athwart path than along the fore-aft path, $t(15) = 3.52$, $p = .003$. Performance also differed between the path directions: Participants walked further along the athwart path than along the fore-aft path, $t(15) = 2.74$, $p = .015$. The accuracy of judgments (mean judged walkable distance/mean actual walked distance) did not differ between the athwart path (mean proportion = 0.839, 95% CI 0.57 < mean < 0.97) and the fore-aft path (mean proportion = 0.775, 95% CI 0.50 < mean < 0.94), $p = .98$. Finally, the 95% confidence intervals reveal that, for both the fore-aft and athwart paths judged walkable distance was less than actual walkable distance.

The visual appearance of the athwart path was the same in both directions; that is, when walking toward port as compared to when walking toward starboard. By contrast, the visual appearance of the fore-aft path differed as a function of direction. The “view” when walking toward the bow included the upper decks, effectively blocking much of the horizon (see Fig. 2), whereas when walking aft the horizon was plainly visible. Whether or not people look at it, simply having the horizon in view reduces the magnitude of standing body sway at sea (Mayo et al. 2011). For this reason, we felt it was appropriate to evaluate the possibility that walking performance might have differed as a function of walking direction along each of the two paths. Separately for each walking path, we used paired samples *t* tests to compare walking performance as a function of direction. For the athwart path, the effect of walking toward port versus starboard was not significant, $t = 1.09$, $p = .17$. For the fore-aft path, the effect of walking toward the bow versus the stern was not significant, $t = 0.60$, $p = .61$. That is, we found no evidence that walking performance was influenced by visual differences associated with walking in different directions along each path. A similar analysis for affordance judgments would have been meaningless, due to the fact that all judgments were made from the starting plate (Fig. 3a, b).

Discussion

On a ship at sea, participants (experienced maritime crewmembers) judged the distance that they could walk along narrow paths laid out on the open deck. One path was parallel with the ship's fore-aft axis, while the other was parallel with the ship's athwart axis. Under mild sea conditions, ship motion was greater in roll than in pitch, such that walking along the fore-aft axis was more challenging than walking along the ship's athwart axis. Participants judged that they could walk further along the athwart path than along the fore-aft path. Actual walking performance (evaluated after the completion of judgments) differed between the paths and was consistent with the judgments. The accuracy of judgments (relative to actual walking performance) did not differ between the two directions. We argue that differential ship motion in roll and pitch created differential affordances for locomotion along these two axes and that participants accurately detected these differences.

Walking performance

Actual walking performance differed between the fore-aft and athwart paths, that is, as a function of direction relative to the ship. The difference was in the expected direction (athwart performance > fore-aft performance), consistent with the hypothesis that the control of lateral oscillation was more greatly challenged when walking fore-aft than when walking athwart. This result is consistent with an earlier finding that step timing is more strongly affected by ship motion in roll than by ship motion in pitch (Haaland et al. 2015) and is consistent with similar effects in the context of standing body sway (Chen and Stoffregen 2012; Munafo et al. 2015; Varlet et al. 2015). It is important to emphasize that these effects do not suggest a differential effect of roll versus pitch motion, as such. Rather, the observed effects arise from the fact that, in most cases the magnitude of motion is greater in roll than in pitch. Accordingly, we predict that the effects observed in our study could be replicated in a future study in which walking was always in the same direction (e.g., always athwartship), but the independent variable was changes in sea state (i.e., weather-dependent changes in the magnitude of angular ship motion).

Affordance judgments

We compared judgments of walking ability as a function of walking direction, relative to the ship. Judgments of walking ability along the fore-aft and athwart paths differed significantly, and the difference was in the expected direction (athwart judgments > fore-aft judgments). This result constitutes the first demonstration of sensitivity to affordances in the moving nautical setting. In our study, the same participants, standing in the same place on the same ship, varied their judgments of their own walking ability solely as a function of facing one direction rather than another, relative to the ship. The static properties of the deck did not vary as a function of direction; only its dynamic properties differed between fore-aft and athwart. Accordingly, our results are consistent with the hypothesis that participants were sensitive to these dynamic affordances.

We evaluated the accuracy of affordance judgments in terms of how judgments differed from actual performance (judged/actual). The accuracy of affordance judgments did not differ between the fore-aft and athwart paths. That is, the fact that ship motion was greater in roll than in pitch affected walking ability, and it affected judgments of walking ability, but it did not affect participants' ability to detect (judge) their walking ability. We take this overall pattern of results as evidence for the hypothesis that participants were sensitive to affordances, rather than basing their judgments on the magnitude of ship motion, as such.

For both directions, judged walkable distance was less than actual walkable distance, as shown by the fact that the 95% confidence intervals for the judged/actual ratio did not include 1.0. These differences might be interpreted as under-estimates which, in turn, could be interpreted in terms of a "safety margin" in affordance perception (cf. Warren and Whang 1987). We view these interpretations as unlikely (cf. Franchak et al. 2012). In this study, we first familiarized participants with the walking paths by asking them to walk comfortably along each path. At this point, participants did not know that we would ask them to estimate their ability, and they did not know that we would (later) conduct a formal evaluation of their ability. During the judgment phase, we asked participants to judge walking ability if they were to walk comfortably (as they had done during the familiarization phase). We have no reason to believe that they did not follow our instructions when making judgments. By contrast, in evaluating actual walking ability, participants often did not honor our request to walk comfortably. Rather, in many cases, it was unmistakably clear that participants exerted active, deliberate (i.e., not "comfortable") efforts to keep their feet within the edges of the paths. That is, participants appeared to have *judged* their "comfortable walking ability", but to have *actualized* their "best" walking ability. If this is true, it would explain (indeed, it would predict) our finding that the ratio of judgments to performance was less than 1.0.

We did not include a control condition in which ship motion was absent. That is, we did not ask participants to judge affordances for walking in different directions under terrestrial conditions (i.e., at the dock). We took as given the idea that, in the absence of ship motion, participants would (correctly) perceive the distinction between walking along the fore-aft and athwart paths to be inconsequential, or meaningless. On land, when the ground is flat, rigid, and uniform (like the steel deck of our ship), facing and walking in one direction versus another is a meaningless variable; that is, it has no effect on affordances for walking (cf. Chen and Stoffregen 2012). The rolling gait that typifies mariners on land rapidly fades (usually within 24 h) as they revert to their "land legs" (e.g., Stevens and Parsons 2002). Before our voyage began, the ship had been in port for more than 2 weeks; thus, we can be certain that all participants had fully adjusted to terrestrial conditions. If it is accepted that participants could detect the fact that terrestrial affordances for locomotion were constant with respect to direction, then our results indicate sensitivity to the difference in affordances between land and sea, that is, to the fact that angular ship motion changes actual affordances for walking.

We chose experienced mariners as participants owing to the novelty of our study. To the best of our knowledge, no previous experimental studies have addressed the possibility that humans might be sensitive to the moment-to-moment changes in constraints that characterize affordances for bodily activity on ships at sea. An important goal of our study was, therefore, to ascertain whether any such capability existed, and for this reason it seems prudent to use as participants individuals who would have the greatest possible likelihood of exhibiting sensitivity to affordances of this kind. Accordingly, it is likely that performance in our study was influenced by knowledge gleaned from our participants' long maritime experience. The success of our "best-case scenario" motivates future research in which it will be important to determine the nature of participants' sensitivity (e.g., the relative importance of immediate perceptual information versus responses acquired through previous experience), to evaluate changes that occur as participants adapt to life on a moving surface (that is, as they "get their sea legs"), and so on. Novice mariners rapidly adapt the kinematics of standing body sway to constraints arising from ship motion (Stoffregen et al. 2013). As part of this rapid adaptation, they appear to learn to use the nautical horizon as a referent for postural control (cf. Mayo et al. 2011). In future research, it will be important to track simultaneously changes in affordance perception and changes in the kinematics of posture and gait. Such coordinated monitoring can help us to understand how it is that participants learn about changes in affordances that emerge from the dynamics of ship motion (cf. Mark 1987; Mark et al. 1990; Yu et al. 2011).

Conclusion

On a ship at sea, angular motion was greater in roll than in pitch. Ship motion in pitch would tend to affect lateral variation in gait when walking parallel to the ship's athwart axis, and ship motion in roll would tend to affect lateral variation in gait when walking parallel to the ship's fore-aft axis. We asked experienced mariners to judge their ability to walk along defined paths that were aligned with the ship's fore-aft and athwart axes. Participants judged that they could walk further along the path that was aligned with the ship's athwart axis, that is, they judged that the affordance for walking was greater when walking was constrained by ship motion in pitch. Subsequent testing confirmed that actual walking ability (the distance that could be walked while remaining within the paths) was greater when walking along the athwart path than when walking along the fore-aft path. That is, in qualitative terms, the difference in mean judgments between the two path directions correctly mirrored the direction-specific difference in actual affordances. Finally, the accuracy of judgments (the ratio of judgments to measured ability) did not differ as a function of direction. Taken together, these results suggest that experienced mariners were sensitive to the fact that affordances for walking were differentially affected by ship motion in roll versus pitch.

Behavior happens on vehicles, as well as on the surface of the Earth: cars, aircraft, surfboards, escalators, bicycles (e.g., Plumert et al. 2004), and ships at sea. Our experiment motivates the study of affordances that are related to vehicular travel and, more generally, to the fact that behavior often is governed by forces other than (or in addition to) gravity (Stoffregen and Bardy 2001; Stoffregen and Riccio 1988; Stoffregen et al. 2013).

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