



Full Length Article

Adaptive perception of changes in affordances for walking on a ship at sea

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ABSTRACT

Ocean waves cause oscillatory motion of ships. Oscillatory ship motion typically is greater in roll (i.e., the ship rolling from side to side) than in pitch (i.e., tipping from front to back). Affordances for walking on a ship at sea should be differentially influenced by ship motion in roll and pitch. When roll exceeds pitch, the maximum walkable distance within a defined path should be greater when walking along the ship's short, or athwart axis than when walking along its long, or fore-aft axis. When pitch exceeds roll, this relation should be reversed. We asked whether such changes in ship motion would be reflected in judgments of direction-specific affordances for walking. Participants (experienced maritime crewmembers) judged how far they could walk along a narrow path on the ship deck. On different days, sailing conditions were such that the relative magnitude of pitch and roll was reversed. Judgments of direction-specific affordances for walking mirrored these changes in ship motion. The accuracy of judgments was consistent across directions, and across changes in ship motion. We conclude that experienced maritime crewmembers were sensitive to dynamic variations in affordances for walking that were, themselves, a function of dynamic properties of the animal-environment system.

1. Introduction

Affordances are possibilities for action that exist for a given animal in a given environment (Gibson, 1979; Stoffregen, 2003). For example, affordances for locomotion emerge from relations between properties of an animal and properties of the environment that allow for movement from place to place (e.g., Lee, Young, & McLaughlin, 1984; Plumert, Kearney, Cremer, Recker, & Strutt, 2011). One type of locomotion is walking.

Walking necessarily includes lateral oscillations of the body as weight shifts between the feet. These lateral oscillations can influence relations between the animal and properties of the environment, that is, affordances. As one example, consider walking through doorways. One might think that the narrowest doorway that a person can walk through (without rotating their shoulders) would be equivalent to shoulder width, that is, the static width of the body. However, lateral oscillations in walking mean that doorways must be (at least) the “dynamic width” of the body in walking. People appear to be sensitive to this requirement: Judgments of the minimum width of a doorway for “walking through” are larger than static shoulder width, but match very well with the dynamic width of the body in motion (Franchak, Celano, & Adolph, 2012; cf. Higuchi, Takada, Matsuura, & Imanaka, 2004; Warren & Whang, 1987).

As an architectural feature, the width of any given doorway tends to be constant, such that in walking through doorways the

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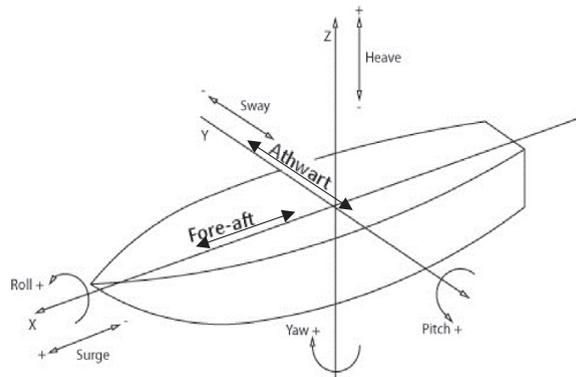


Fig. 1. Ship motion occurs in six degrees of freedom. Angular ship motion comprises roll, pitch, and yaw, while translational ship motion comprises surge, sway, and heave. The figure also indicates the ship's fore-aft and athwart axes.

person's own movement is the only dynamic aspect of the situation. Consequently, the ability to walk through a doorway emerges from the relation between the (static) width of the door and the (dynamic) width of the body. In other situations, relevant aspects of the environment may also be dynamic, such that affordances for walking emerge from relations between dynamic properties both of the person and of the environment. For example, motion of the ground surface can influence affordances for walking. Consider walking on subway or train cars, or stepping onto or off of moving walkways that often are found in large airports. These transitions often cause momentary but very noticeable changes in gait. In several studies, researchers have manipulated the fit between properties of perceiver and environment and have investigated perception of consequent changes in affordances for locomotion (e.g., Franchak et al., 2012; Higuchi, Cinelli, Greig, & Patla, 2006; Mark, 1987; Mark, Balliet, Craver, Douglas, & Fox, 1990). However, in those studies, changes in affordances were relatively discrete. Such studies do not address (changes in) perception of affordances as a consequence of dynamic, continuous variation in the fit between perceiver and environment. Other studies have investigated the perception of affordances for the timing of locomotion; for example, walking or cycling through temporal gaps in automobile traffic (e.g., O'Neal et al., 2018; Plumert et al., 2011). Existing laboratory research has not addressed how motion of the support surface can influence locomotor affordances, or whether such influences can be perceived.

1.1. Affordances relating to ship motion

In the present study, we investigated perception of affordances that emerged from relations between dynamic properties of participants (their ability to modulate lateral oscillations in walking) and dynamic properties of the surface of support (angular motion of a ship at sea). Motion of the ocean's surface (swells and waves) gives rise to oscillatory ship motion in six degrees of freedom (df); three of rotation (roll, pitch, and yaw), and three of translation (surge, sway, and heave); (Fig. 1). These highly complex oscillations are concentrated below 0.2 Hz (e.g., Stoffregen, Villard, & Yu, 2009). Ship motion induces broad changes in gait that are sufficiently general that they can be seen by casual observers, such as the "rolling gait" that characterizes experienced mariners at sea (Stevens & Parsons, 2002). Given these effects, variations in ship motion might be used to investigate mariners' perception of how walking affordances are influenced by motion of the ground surface. Although the experimenter cannot generally exercise control over ship motion, regularities in naval architecture provide natural constraints on ship motion. In general, ships are longer than they are wide. Consequently, ship motion typically is greater in roll (about the ship's fore-aft, or front-back axis) than in pitch (about the ship's athwart, or side to side, axis); (see Fig. 1). At sea, the kinematics of upright stance differ dramatically when participants stand facing in different direction, such as fore-aft versus athwart (Chen & Stoffregen, 2012; Munafo, Wade, Stergiou, & Stoffregen, 2015; Varlet et al., 2014, Varlet, Bardy, Chen, Alcantara, & Stoffregen, 2015). In addition, in walking on a ship at sea the variability of stride time intervals differs between walking along the ship's fore-aft versus athwart axes (Haaland, Kaipust, Wang, Stergiou, & Stoffregen, 2015).

Walter, Wagman, Stergiou, Erkmén, and Stoffregen (2017) investigated sensitivity to affordances for walking on a ship at sea that arose solely from differential angular motion of the ship around its short (i.e., pitch) and long axes (i.e., roll). When walking athwartship (i.e., from port to starboard, and vice versa), side-to-side oscillation of the body in gait is influenced primarily by ship motion in pitch. When walking fore-aft (i.e., toward the bow, or stern), lateral oscillation is influenced primarily by ship motion in roll. In their study, as is typically the case on a ship at sea, roll was greater than pitch. Therefore, Walter et al., predicted that participants would be able to walk farther without stepping outside of the boundaries along a narrow path when walking athwart than when walking fore-aft. In addition, they predicted that experienced mariners would be sensitive to such direction-specific differences in walking ability, such that judgments of walking ability fore-aft versus athwartship would prospectively reflect differences in actual walking ability in these two directions. As predicted, participants judged that they could walk further along the athwart path than along the fore-aft path. Subsequent performance (actual walking along those same paths) was consistent with judged ability. The accuracy of judgments, that is, the ratio of judgments to performance, did not differ between directions.

Walter et al. (2017), interpreted these results as indicating that experienced mariners were prospectively sensitive to affordances

for walking in different directions, where direction-specific differences in actual walking ability arose exclusively from the direction-specific variations in the dynamic properties of ship motion, that is, in the relative magnitude of pitch and roll.

1.2. Changes in sea state qualitatively change affordances for gait

Walter et al. (2017) found that perception of affordances for walking on a ship at sea reflected the fact that ship motion is generally greater about the fore-aft axis than about the athwart axis (roll > pitch). However, while ship motion is largely a consequence of ship architecture, it also depends on sailing conditions. Under most sailing conditions (and as was the case in Walter et al., 2017), roll is greater than pitch. However, heading directly into a consistent, simple, unidirectional swell will tend to cause pitch to be greater than roll. The latter situation is rare. It might be that experienced mariners' knowledge of nautical walking is related to the static fact that the ship is longer than it is wide, or to expectations about the typical dynamic state in which pitch is greater than roll. Alternately, experienced mariners might be sensitive to how affordances for walking are influenced by variations in ship motion, which is influenced by both ship architecture and sailing conditions. In the present study, we asked whether perception of affordances for walking would reflect qualitative changes in ship motion occurring under different sailing conditions. Specifically, we asked whether perception of affordances for nautical walking would reflect constraints imposed by ship motion in the atypical case in which ship motion was greater in pitch than in roll.

Using a within-participants design, on a long cruise we selected for testing days that differed in sailing conditions such that they affected oscillatory ship motion. On one day (which happened to be the second day of testing), the relative magnitude of pitch and roll closely resembled Walter et al. (2017); that is, the more typical conditions in which roll > pitch. On this day, we expected to replicate the direction-specific effects that were reported by Walter et al. That is, we expected that participants would judge that they could walk farther along the athwart path than along the fore-aft path, and that judgments would accurately reflect actual performance. On the other day (which happened to be the first day of testing), the relative magnitudes of pitch and roll were reversed, such that pitch > roll. Under this condition, we predicted that participants would judge that they could walk further along the fore-aft path than on the athwart path, and that judgments would accurately reflect actual performance.

Under both patterns of ship motion (i.e., roll > pitch, and pitch > roll), we predicted that mean judgments of walking ability would differ across walking directions (i.e., walking fore-aft vs. walking athwartship). Our central prediction was that the nature of this difference would itself differ across ship motion conditions, such that the Ship Motion \times Walking Direction interaction would be statistically significant. With respect to the accuracy of judgments, our prediction was that any changes in judgment accuracy would be independent of our predicted effects in mean judgments, and independent of any changes in the overall magnitude of ship motion.

We built on and expanded the work of Walter et al. (2017) not only by collecting data across sailing conditions that differentially affected oscillatory ship motion but also by quantitatively verifying such differences in ship motion. To confirm that roll actually exceeded pitch, Walter et al. relied upon the expert opinion of the ship's officers. In the present study, we obtained (and statistically analyzed) quantitative data on angular ship motion during the hours of data collection. These data allowed us to provide objective confirmation of the relative magnitude of angular ship motion in roll and pitch. This confirmation was critical for verification of our manipulation, across testing days, of the relative magnitude of pitch and roll.

Our study was conducted in the field, which necessarily reduced the level of experimental control that we could exert. We could not control the weather or the motion of the ship. However, following other field studies (Jacobs & Hawley, 2007; Mayo, Wade, & Stoffregen, 2011; Stevens & Parsons, 2002) we felt that the reduction in experimental control was necessary to address the issues at hand.

2. Method

2.1. Participants

Our sample comprised 13 individuals (9 men and 4 women), ranging in age from 22 to 58 years (mean = 39.15 years), in height from 1.45 to 1.91 m (mean = 1.76 m) and in weight from 54.43 to 92.99 kg (mean = 75.3 kg), and with 1–40 years (mean = 13.23 years) experience working at sea. Participants were working crew members who volunteered (with the Captain's permission), taking time off from their regular duties. None of these individuals had participated in our earlier study (Walter et al., 2017). 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, and written informed consent was obtained from each participant. To ensure a large enough sample size to provide sufficient power reliably to exclude false rejection of the null hypothesis, we tested power ($1-\beta$) with the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007), using the *a priori* option and the effect size (0.81) for affordance judgments from Walter et al. (2017; $n = 16$). Power analysis revealed a test power of 0.967 and suggested that a sample size of $n = 10$ would be sufficient to achieve the desired effect size of 0.81.

2.2. Setting

The study was conducted during a 16-day cruise aboard the R/V Atlantis, from Puntarenas, Costa Rica to Woods Hole Massachusetts, USA. The ship was 84 m long with a 26 m beam. It displaced 3500 tons, and cruised at 10–12 knots.

The ship's equipment included an inertial measurement unit (IMU), a standard device that measured and recorded the ship's

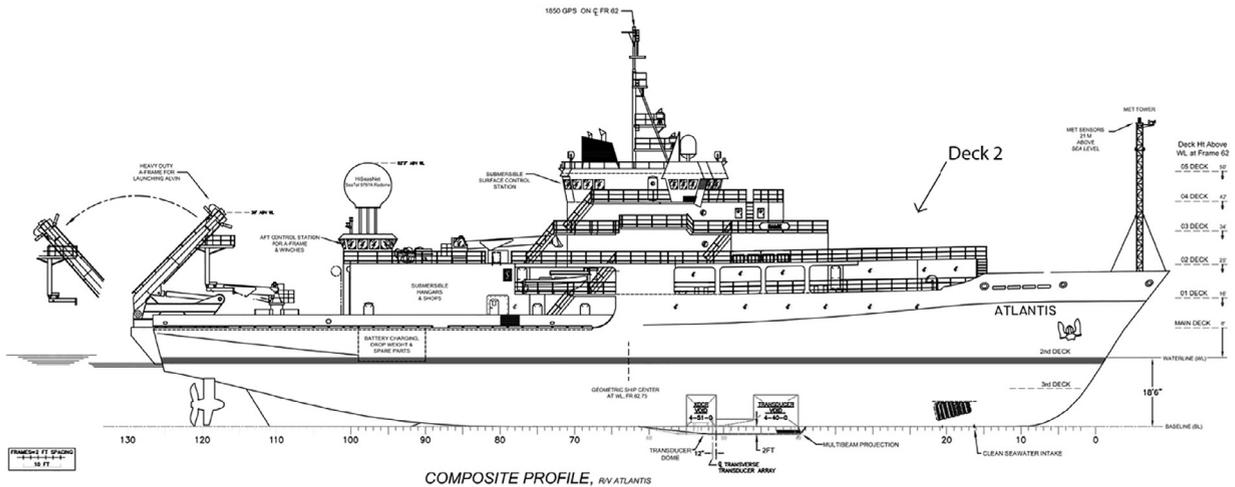


Fig. 2. The R/V Atlantis. The arrow indicates the portion of Deck 2 on which the study was carried out.

angular motion in each of the six df. From the IMU, we obtained data on the magnitude of roll and pitch. The IMU was sampled at 1 Hz. We analyzed ship motion in pitch and roll during the hours of data collection, and summarized these data for each day of testing.

2.3. Procedure

The ship departed Puntarenas, Costa Rica on June 14, 2017 and arrived in Woods Hole Massachusetts, USA on June 30. The data were collected on Sunday June 18 and Sunday June 25. On each day, data were collected during full daylight, between 9:00 and 17:00.

Testing was conducted on the second deck of the ship, which was free from clutter (Figs. 2 and 3). Two pathways (each 8.9 m long × 0.3 m wide) were created at 90° using clearly visible tape. One pathway was marked along the long (fore-aft) axis, and the other was marked along the short (athwart) axis (Figs. 3 and 4). Judgment data were collected with the participant standing at the intersection of the two pathways. At this starting location, participants stood with their feet on the taped lines. The purpose was to standardize foot position to reduce variation in the walking distance. The length and width of each path was the same used by Walter et al. (2017). We used a within-participants design, in which each individual participated on both days. The methods and procedure were identical on the two testing days.

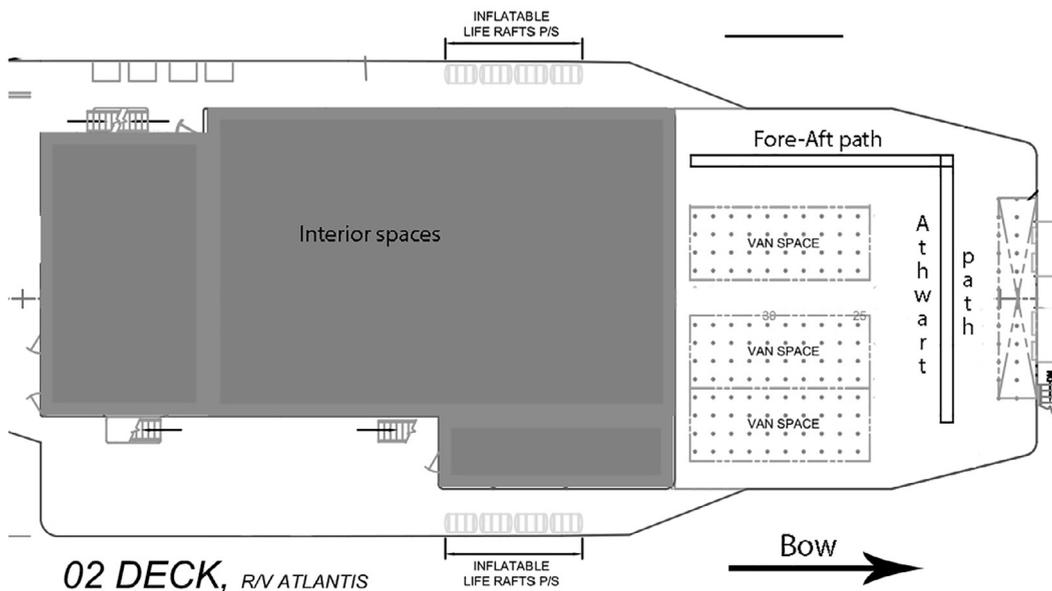


Fig. 3. Overhead view of the forward portion of Deck 2, illustrating the placement of the walking paths on the open deck.



Fig. 4. The athwart path (left) and the fore-aft path (right).

2.3.1. Familiarization phase

Participants wore shoes in compliance with ship regulations. Beginning at the paths' intersection, participants were asked to walk comfortably along the marked paths while ignoring the lines: "Keep your eyes on the end line, ignore the parallel lines, and walk comfortably to the end line". Participants were required to walk out and back twice along each of the paths. The purpose of the familiarization phase was to ensure that participants were comfortable traversing the marked paths that we had created, *not* to provide practice at walking in different directions. Given that participants were experienced mariners and that the first day of data collection was the 5th day of the voyage (such that participants had already performed thousands of steps in multiple directions all over the ship, cf. Chang et al., 2015), it is unlikely that the familiarization phase provided (additional) information that participants used in making their judgments. Also, in the familiarization phase participants walked the full length of the paths without interruption, without any feedback about performance, and (on the first day of testing) without knowing that we were going to ask them to judge their ability to walk within the paths.

2.3.2. Judgment task

After familiarization, participants stood at the path intersection and estimated how far they could walk along each path without stepping on or over the marked lines. On each trial, the participant was asked to look at the designated path and estimate "if you were walking comfortably, how far do you think you could walk along this path without stepping on or over the lines?" To report estimated distance, the participant instructed an experimenter where to place a marker (a 0.25 m length of a wooden 4×4) along the path. At the beginning of the trial, the experimenter stood near the participant, facing them, and slowly walked backward along the path until instructed to stop by the participant. 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.

2.3.3. Performance (walking) task

After completing the judgment task, participants were asked to walk comfortably along each of the paths: "Please do not look at your feet. Keep your eyes on the end of the path 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 intersection point), with each length constituting one performance trial. If the participant stepped on or over the lines with any part of either foot, it was classified as a "fault" and the walked distance was recorded from the spot of the fault (see [supplementary materials](#)). Each of three experimenters watched for faults, with one experimenter on each side, walking behind so as to be able to monitor footfalls, and so as to be outside the participant's field of view, and one experimenter remained at the starting point.

Because ours was a field study in which the essential independent variable was a function of sea conditions, it was not possible for us to counter-balance the order of presentation of the different ship motion conditions.

3. Results

On the first testing day, the ship maintained a constant heading NE, directly into a consistent 2 m swell from the NE. The sea state

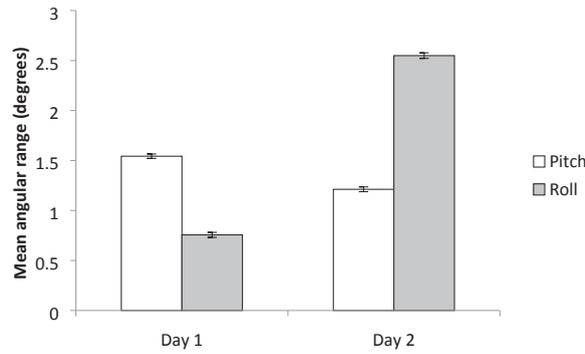


Fig. 5. Angular ship motion (mean range of oscillation cycles, in degrees), illustrating the statistically significant interaction between motion direction (Pitch vs. Roll), and testing days (Day 1 vs. Day 2). Error bars represent the 95% confidence interval of the mean.

was 2.5 on the Beaufort Scale (Beer, 1997). On the second testing day, the ship maintained a constant heading north, which put it at a constant angle relative to a 2 m swell from the SW. The sea state was 4.0 on the Beaufort Scale. Anecdotally, during the familiarization phase participants' gait appeared to be natural, and comfortable. By contrast, during the walking performance trials (i.e., after completing judgments), participants often made visible efforts to maximize their performance, such as waving their arms or shortening their stride. That is, in their actual walking performance they appear to have tried to “walk as far as possible”, rather than to “walk comfortably”. We did not exclude these trials from our analysis.

3.1. Ship motion

From raw data on ship motion, we computed the range of angular motion for each oscillation cycle. We used the *findpeaks* function in Matlab to identify the maximum excursion for each oscillation cycle, separately in pitch and roll. For each oscillation cycle, the difference between successive peaks was the range of motion for that cycle. We subjected these ranges to a 2×2 ANOVA with factors Days (Day 1 vs. Day 2) and Motion Direction (Pitch vs. Roll). In the ANOVA, the degrees of freedom reflect the number of oscillation cycles.

Data on the motion of the ship are summarized in Fig. 5. The main effect of days was significant, $F(1,21,987) = 3278.34$, $p < .001$, partial $\eta^2 = 0.13$, reflecting the increase in overall ship motion between June 18 (sea state = 2.5) and June 25 (sea state = 4.0). The main effect of motion was significant, $F(1,21,987) = 451.39$, $p < .001$, partial $\eta^2 = 0.02$, with greater overall motion in roll than in pitch. In addition, the Day \times Motion interaction was significant, $F(1,21,987) = 6956.11$, $p < .001$, partial $\eta^2 = 0.24$, showing greater pitch than roll on Day 1 (June 18) and greater roll than pitch on Day 2 (June 25). As can be seen from the effect sizes, the statistically significant interaction accounted for the majority of the variance.

3.2. Mean judgments

The judgment data are summarized in Fig. 6. For each Ship Motion condition, we calculated means for the two judgments of the fore-aft path, and for the two judgments in the athwart path. We conducted a 2×2 repeated measures ANOVAs on these values with factors Ship Motion (Day 1: Pitch > Roll vs. Day 2: Roll > Pitch) and Walking Direction (Fore-aft vs. Athwart). To account for our use of a within-participants design, for statistically significant effects we estimated effect size using the *F*-value and its degrees of freedom (Lakens, 2013; Eq. (13)). Similarly, we computed effect sizes for post-hoc *t*-tests using Cohen's d_z (Lakens, 2013; Eq. (7)). The

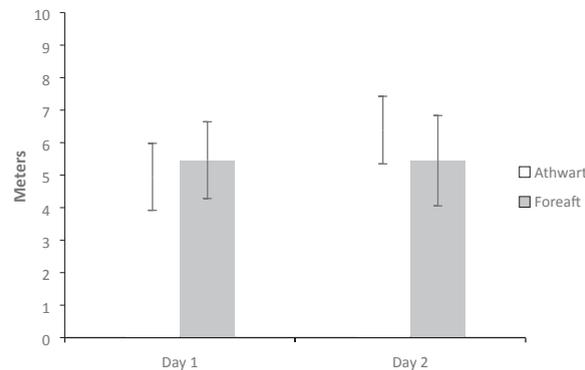


Fig. 6. Mean judgments of walking ability along the fore-aft and athwart paths as a function of ship motion (pitch > roll vs. roll > pitch). Error bars represent the 95% confidence interval of the mean.

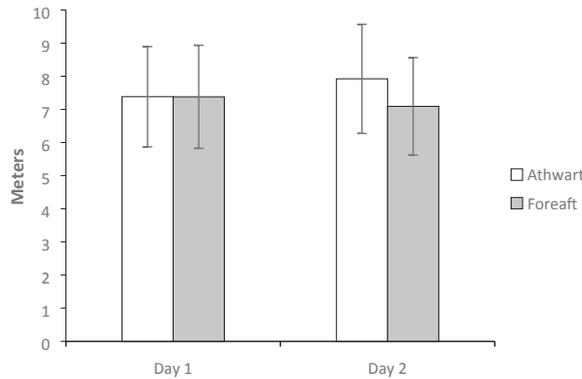


Fig. 7. Performance (mean walked distance) along the fore-aft and athwart paths as a function of ship motion (Day 1: pitch > roll; Day 2: roll > pitch). Error bars represent the 95% confidence interval of the mean.

ANOVA revealed that only the Day \times Direction interaction was significant, $F(12) = 7.87$, $p = .016$, partial $\eta^2 = 0.40$. When pitch > roll (Day 1), participants judged that they could walk further along the fore-aft path than along the athwart path, $t_{(12)} = 2.56$, $p = .04$, $d_z = 0.71$ (see Lakens, 2013). When roll > pitch (Day 2), participants judged that they could walk further along the athwart path than along the fore-aft path, $t_{(12)} = 2.26$, $p = .04$, $d_z = 0.63$. Five participants gave the maximum judgment (890 cm) for each judgment in each direction; that is, they exhibited a ceiling effect.

3.3. Walking performance

For performance trials, we took the mean of the six trials for the fore-aft path, and for the athwart path. We conducted 2×2 repeated measures ANOVAs with factors Days (Day 1 vs. Day 2) and Direction (fore-aft vs. athwart paths). The data are summarized in Fig. 7. The ANOVA revealed no significant effects. Despite this outcome, for comparison with Walter et al. (2017), we conducted planned comparisons of effects of walking direction on each testing day. For walking performance on Day 1, the effect of direction was not significant, $t(12) = 0.01$, $p > .05$. For Day 2, performance was better (i.e., participants walked farther) when walking along the athwart path than when walking along the fore-aft path, $t(12) = 2.49$, $p = .03$.

3.4. Judgment accuracy

The data are summarized in Fig. 8. To evaluate the accuracy of judgments, we expressed judgments as a proportion of actual walking performance (judgment mean/performance mean). As can be seen in Fig. 8, on Day 1 the 95% confidence intervals included 1.0 for both walking directions. By contrast, on Day 2, the 95% confidence intervals did not include 1.0, for either walking direction. However, the figure also reveals that the two days differed in the size of the confidence intervals, due to the fact that the standard error of judgment/performance ratios on Day 1 was 2–4 times greater than the standard errors on Day 2.

To determine whether accuracy varied as a function of conditions, we compared these proportions using a 2×2 ANOVA with factors Ship Motion (pitch > roll vs. roll > pitch) and Direction (fore-aft vs. athwart paths). The ANOVA yielded no significant effects. That is, we found no evidence that judgment accuracy differed as a function of days, or as a function of walking direction.

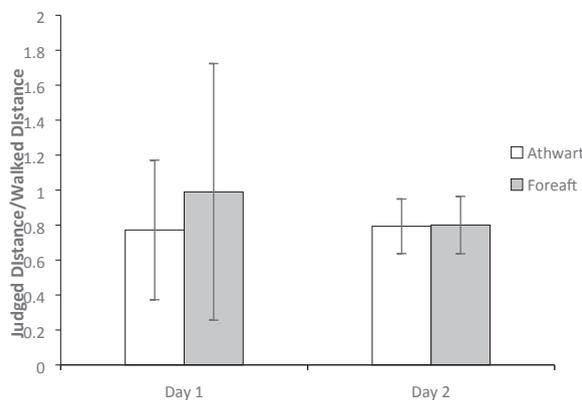


Fig. 8. Mean accuracy of walking judgments (judgment/performance) for the fore-aft and athwart paths as a function of ship motion (Day 1: pitch > roll; Day 2: roll > pitch). Error bars represent the 95% confidence interval of the mean.

4. Discussion

On a ship at sea, we asked experienced maritime crewmembers to judge how far they could walk while remaining within the boundaries of marked paths. One path paralleled the ship's long (fore-aft) axis, while another paralleled the ship's short (athwart) axis. Walking in the two directions was differentially constrained by variations in the relative magnitude of angular ship motion in pitch and roll, created by a combination of ship architecture and sailing conditions. Judgments of walking ability differed as a function of walking direction (i.e., along the fore-aft and athwart paths), and the direction of this difference depend on sailing conditions. Consistent with our predictions, when pitch was greater than roll (Day 1), participants judged that they could walk farther along the fore-aft path than along the athwart path, and when roll was greater than pitch (Day 2), participants judged that they could walk farther along the athwart path than along the fore-aft path. That is, building on the results of [Walter et al. \(2017\)](#), we found that perception of affordances for walking on a ship at sea not only reflected patterns of ship motion occurring under typical sailing conditions (Day 2) but also reflected the *qualitative reversal* in such patterns occurring under atypical sailing conditions (Day 2).

4.1. Adaptive perception of differing constraints

It might be that experienced mariners' knowledge of affordances for nautical walking is related to their existing knowledge that the ship is longer than it is wide, and/or to previous experience of typical sailing conditions in which pitch is greater than roll. Alternately, experienced mariners might flexibly and spontaneously exhibit sensitivity to how (both typical and atypical) patterns of ship motion influence their ability to walk on the open deck. If so, then experienced mariners' judgments of affordances for nautical walking should change with changes in relevant parameters of ship motion. In the present study, our primary prediction was that perception of affordances for walking along the fore-aft and athwart paths would be influenced by changes in the relative magnitude of angular ship motion in pitch and roll across sailing conditions. We were fortunate to experience days at sea in which the relative magnitude of ship motion in roll and pitch differed qualitatively ([Fig. 5](#)). This occurrence permitted us to ask whether participants were sensitive to changes in affordances for walking that arose from these naturally occurring changes in ship motion and *that reversed the typical relative magnitudes of pitch and roll* (see [Walter et al., 2017](#)). The judgment data make clear that this was so (compare [Figs. 5 and 6](#)), confirming our prediction. That is, experienced mariners judged that their direction-specific walking ability varied in relation to actual variations in the relative magnitude of pitch and roll. That perception of affordances for walking on a ship at sea reflected qualitative differences in ship motion occurring under both typical and atypical sailing conditions is the principal result of our study. The results of [Walter et al. \(2017\)](#) indicated that experienced mariners were sensitive to affordances arising from dynamics of the body and the ship. In the present study, our results indicate that experienced mariners were sensitive to the dynamics of those dynamics.

Overall, participants judged that they could walk further when roll > pitch than when pitch > roll ([Fig. 6](#)). This was true despite the fact that overall ship motion was greater in the former case than in the latter ([Fig. 5](#)). Especially in light of differences in variability of accuracy across such conditions ([Fig. 8](#)), this pattern of results is likely an effect of the relative novelty of sailing conditions in which pitch > roll (such as on Day 1). The finding that walking direction always influenced judgments of walking ability suggests that participants detected the *nature* of influence of ship motion on walking affordances in both ship motion conditions, but that in the less familiar motion condition (pitch > roll) they may have been less able to detect the *magnitude* of the effect.

On Day 2, roll was greater than pitch, as was the case in the study of [Walter et al. \(2017\)](#). The results on this day of testing directly replicated the effects reported by Walter et al., on a different ship, in a different sea, with different participants. The actual values of the judgments also were similar, as can be seen by comparing the right side of [Fig. 6](#) from the present study with the left side of [Fig. 4](#) from Walter et al. In the Condition \times Direction interaction, the effect sizes for the post-hoc *t*-tests were very similar to those reported by [Walter et al. \(2017\)](#); $d_z = 0.98$. These large effect sizes testify to the profound influence of ship motion on human behavior (especially walking behavior), and are consistent with findings from previous studies. For example, [Chen and Stoffregen \(2012\)](#) evaluated the kinematics of standing body sway when participants stood facing the ship's bow (front), or its port (left side, when facing the bow). With a sample size of only 9, this simple manipulation yielded a statistically significant effect with an effect size of partial $\eta^2 = 0.81$. In other studies of standing posture at sea, effect sizes (partial η^2) up to and exceeding 0.90 have been observed (e.g., [Stoffregen, Chen, Varlet, Alcantara, & Bardy, 2013](#); [Varlet et al., 2014, 2015](#)).

At sea, oscillatory motion of ships has powerful effects upon human performance. As noted by [Stevens and Parsons \(2002, p. 29\)](#); cf. [Wertheim, 1998](#)), "ship motions limit a crews' ability to perform essential command, control, and communications functions, navigation tasks, maintenance responsibilities, and even the preparation of food". For crew members who are standing or walking, effects of ship motion have been most closely studied in the context of *motion-induced interruptions*, or *MII* ([Crossland et al., 2007](#)). Analyses of MII have focused exclusively on the physical dynamics of ship motion in relation to an hypothetical "tipping point" for the body ([Graham, 1990](#)). In analyses of human movement at sea, little attention has been paid to psychological characteristics of crew members, including skill-related aspects of performance, or crew members' knowledge of their ability to stand and walk under different conditions. In the present study, we investigated crew members' knowledge of their walking abilities as a function of natural variations in the angular motion of a ship at sea.

Across walking directions and across days the static properties of the deck were constant, including its material substance, its topography, the way it reflected light, and so on. Only the dynamic properties of the deck varied, as a function of how the ship moved. Thus, the differences in judgments across variations in ship motion provide evidence that the perception of dynamically-defined affordances was itself dynamic. These results provide empirical support for the general hypothesis that the perception of affordances is an emergent phenomenon—occurring online and in real time and reflecting changes in the dynamic fit between animal

and environment over multiple time scales (cf. Adolph, Robinson, Young, & Gill-Alvarez, 2008; Mark et al., 1990).

On each testing day, we were able to control the order of presentation of the fore-aft and athwart conditions. By contrast, across testing days, we were not able to control the order of presentation of the ship motion conditions (roll > pitch vs. pitch > roll). This, this aspect of our design was unbalanced. Logically, the results might be influenced by the fact that all participants were tested first when pitch > roll, and second when roll > pitch. For example, it might be the case that the experience of judging walking ability when pitch > roll might influence later judgments of walking ability when roll > pitch. While we acknowledge this logical possibility, we regard the possibility of such an influence on our results as highly unlikely. The principal reason is the fact that the two ship motion conditions were separated by a full week (see Section 2.1). During that intervening week, sailing conditions varied naturally, and participants (along with everyone else onboard) were obliged to perceive and control all of their movements relative to these natural variations in ship motion. If it is admitted that mariners in fact perceived their walking ability and used that knowledge to control walking each day, then it seems extremely unlikely that the brief experience of providing explicit judgments of walking ability on Day 1 would have retained any power to influence judgments made a week later.

4.2. Time scales

In our study, pitch and roll motion of the ship occurred over relatively short time scales (i.e., seconds, or individual footfalls), while quantitative and qualitative changes in the relative magnitude of pitch and roll occurred over longer time scales (i.e., days). It might appear, then, that participants calibrated their perception to conform to a particular (relatively stable) set of sea conditions that characterized an entire day. Our results are consistent with this view, but they do not mandate it. Our results also are consistent with at least one alternative view. Variations in the relative magnitude of pitch and roll can occur across days; however, such variations also occur over shorter time scales. One such time scale is minutes or even seconds, as often occurs when a ship turns, changing its heading relative to the prevailing waves and swell. When a ship turns, changes in the relative affordances for walking along the fore-aft versus athwart paths would occur over time scales similar to those relating to both judgments and performance. Our results are consistent with the possibility that perception of changing affordances for walking fore-aft versus athwart, arising from changes in the relative magnitude of pitch and roll, may have occurred over time scales equivalent to those over which the underlying conditions, themselves, were changing (cf., Newell, Liu, & Mayer-Kress, 2001; O’Neal et al., 2018). This hypothesis could be evaluated by testing across controlled changes in a ship’s heading.

4.3. Judgment accuracy

We evaluated the accuracy of affordance judgments by expressing judgments as a proportion of actual performance (judged/actual). On each testing day, the accuracy of affordance judgments did not differ between the fore-aft and athwart paths (Fig. 8). That is, variations in the relative magnitude of roll and pitch affected judgments of walking ability, but did not affect participants’ sensitivity to their walking ability. This result replicates and extends a finding reported by Walter et al. (2017).

When pitch > roll, judgment accuracy was more variable than when roll > pitch (Fig. 8). There are a number of possible explanations for differences between judged and actual abilities (see Wagman, Bai, & Smith, 2016). However, given the relative paucity of situations under which pitch exceeds roll, in our case the most likely explanation is that participants were insufficiently attuned to stimulation patterns that were informative about walking ability under such (unusual) conditions. Consistent with such a proposal, research has shown that, when action capabilities have been altered, repeated experience perceiving affordances for a given behavior is sufficient for improvements in accuracy of such perception (Higuchi et al., 2004; Mark et al., 1990). We predict that such a process underlies perception of affordances at sea. That is, we predict that, given additional judgment trials without practice or feedback, the accuracy of participant’s judgments of walking affordances when pitch > roll would become less variable.

5. Conclusion

Sea travel predates all other forms of non-ambulatory translation. The domestication of horses occurred approximately 6000 years ago (Anthony, 2007), and terrestrial vehicles and aviation are more recent. By contrast, seafaring may extend back 1,000,000 years (Bednarik, 1999). Thus, people (and other animals) have been adjusting perception and action in relation to ship motion for far longer than other modes of transport. Unlike the present day, when we can fly over water, for many centuries, seafaring was the only way to cross oceans. Consequently, many millions of people had no choice but to “get their sea legs”.

On a ship at sea, we asked participants (experienced mariners) to judge their ability to walk along marked paths that were parallel to the long and short axes of the ship. Judgments were made under different sailing conditions that qualitatively altered the relative magnitude of the ship’s angular motion in pitch and roll. Judgments of walking ability in different directions reflected this qualitative shift in the relative magnitude of pitch and roll, confirming that (in experienced mariners) judgments were dynamic, and were affected by actual variations in ship motion. We interpret these results as demonstrating a new type of flexibility and adaptability in the perception of affordances.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.01.002>.

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