Correspondence Between Haptic and Visual Perception of Stand-on-ability: Do Hills Look as Steep as they Feel?

Jonathan Kenealy Doyon
University of Southern Mississippi

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CORRESPONDENCE BETWEEN HAPTIC AND VISUAL PERCEPTION OF STAND-ON-ABILITY: DO HILLS LOOK AS STEEP AS THEY FEEL?

by

Jonathan Kenealy Doyon

A Thesis
Submitted to the Graduate School
and the Department of Psychology
at The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Master of Arts

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December 2016
ABSTRACT

CORRESPONDENCE BETWEEN HAPTIC AND VISUAL PERCEPTION OF STAND-ON-ABILITY: DO HILLS LOOK AS STEEP AS THEY FEEL?

by Jonathan Kenealy Doyon

December 2016

Vision and haptics play a central role in perceiving environmental layout to guide action. Hajnal, Wagman, Doyon, and Clark (2016) demonstrated that visual perception of stand-on-ability is accurate compared to action capabilities, whereas haptic perception of stand-on-ability reliably underestimates action capabilities. This finding contradicts Gibson’s (1979) theory of equivalence in perceptual systems, which suggests that perception should be equivalent regardless of modality. Previous comparisons of visual and haptic perception tested the modalities in isolation. The current experiment directly compares visual to haptic perception of stand-on-ability by using one perceptual system to estimate the other. Observers viewed a surface set to a discrete angle and attempted to match it haptically with a continuously adjustable surface occluded by a curtain, or felt an occluded surface set to a discrete angle then matched it visually with a continuously adjustable visible surface. Results indicated that visual and haptic perceptions of stand-on-ability are equivalent across some measures and analyses: no differences were found between visual, haptic, and action boundaries. Additionally, matching judgments were scaled similarly across conditions. However, some differences do exist and are modulated by action measures of body posture. Such differences demand a recasting of the question regarding equivalence. The correspondence of perceptual systems and the complex intertwining in the perception-action cycle are discussed.
ACKNOWLEDGMENTS

My sincerest thanks to all of the people who helped me reach this stage in my studies, both at the University of Southern Mississippi, and at the University of South Florida.

First, I would like to thank my advisor, Professor Alen Hajnal, without whom I would not have made it this far. His intellectual guidance served as a brightly lit torch in a darkened subterrane of unfamiliar research.

I would like to thank Professors David J. Echevarria and Donald Sacco for their membership in my defense committee. Their mentorship has made incalculable contributions to my development professionally as a research scientist, and informally as a friend and junior colleague.

I would also like to thank Professor Tom Sanocki, to whom I am indebted for helping me pursue this strange scientific adventure. Without his mentorship and encouragement, I may very well have made the foolish mistake of choosing a life outside of academia, safely removed from the tortures of scientific discovery.
DEDICATION

This work is dedicated to my parents, John and Mary Doyon. My infinite love and thanks belong to them. Without their support and endless encouragement, I would never have come this far.
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CHAPTER I - INTRODUCTION

Locomotion for healthy persons involves an ongoing perception-action cycle: the person detects information contained within the environment which then informs his or her actions; the person then moves through the environment in order to detect more information upon which he or she can act; and so on. This process is driven primarily by the perceiver-actor’s visual and haptic systems, with the other systems engaging to a lesser extent. The present research is concerned with the contributions to perception and action that these two primary modalities offer, the differences between each, and how each modality is exploited during the perception-action cycle. Specifically, this thesis is concerned with how vision and haptics both serve the perceiver-actor when perceiving geographic slant and the affordance of stand-on-ability (Fitzpatrick, Carello, Schmidt, & Corey, 1994; Kinsella-Shaw, Shaw, & Turvey, 1992).

The Perception of Affordances

For a person to act upon a given property of the environment, that property must possess a set of qualities that will permit the act. These qualities are both unique to the actor and unique to the environment with respect to the actor; this set of qualities constitutes what J.J. Gibson referred to as an affordance (1979). For example, a surface will afford upright posture and locomotion if that surface is sufficiently extended in space (i.e., there is enough room), if that surface is nearly flat (i.e., not convex or concave), if that surface is nearly horizontal (i.e., not too steep), and if that surface is rigid enough to support the individual’s total weight (i.e., not like water or sand, both of which permit sinking) (Kinsella-Shaw et al., 1992). Affordances are scaled to the actor such that a knee-high surface for an adult will not necessarily afford sitting for a child for whom
knee-high is considerably shorter. Thus, the affordances for sit-on-ability, leap-over-ability, walk-on-ability, or any other action is specified by the interaction between what is offered by the environment and what is offered by the actor’s physical capabilities and bodily proportions. The current research focused on one affordance in particular: the stand-on-ability of various slopes.

The interaction between perceiver-actor and environment specifies the information contained within the ambient energy arrays that may be available to the perceiver (Gibson, 1979). For example, a snake’s survival depends on its ability to detect the presence of prey; this task may be accomplished by monitoring small fluctuations in the local distribution of heat. These fluctuations in the energy array are not accessible to a human who lacks the biological equipment to detect such small-scale changes. Thus, the environment contains information that specifies the presence and location of prey for a snake only due to its physical capabilities; humans cannot perceive such an affordance by sensing changes in the ambient heat distribution, rather they must rely on other ambient arrays (e.g. visual) in order to accomplish tasks or perform actions.

Humans are equipped with perceptual systems that allow for the detection of information contained in various ambient arrays: the visual system can detect the distribution and scattering of light; the haptic system can detect the layout and composition of terrestrial surfaces; the olfactory and gustatory systems can detect the distribution and concentration of various chemical substances; the auditory system can detect perturbations in the surrounding medium (typically air) which results in aural sensations.
Equivalence in Perceptual Systems

According to Gibson (1966) sensory systems are equivalent in nature, i.e., the detected information specifies the same perceptual event, resulting in equivalent perceptual experiences, independent of the particular sensory channel or energy array. For example, consider the perceptual event where an individual must determine his or her proximity to a large fire: the visual system may alert the individual of danger by assessing distance; the olfactory system by detecting fluctuations in the chemical energy distribution (i.e., concentration of smoke); the thermal sensory system by detecting fluctuations in the heat distribution; etc. All of these sensory channels result in the same percept – “There is a large fire and I may be harmed if I do not move.”

Significant empirical support exists for the notion of equivalence among sensory modalities. The pass-through-ability afforded by an aperture has been shown to be specified by equivalent information, delivered through patterns of stimulation in the aural (Gordon & Rosenblum, 2004; Russell & Turvey, 1999) and optic arrays (Warren & Whang, 1987). The reachability of an object has also been shown to be equivalent within the aural array (Rosenblum, Wuestefeld, & Anderson, 1996) and the optic array (Carello, Grososky, Reichel, Solomon, & Turvey, 1989). Closely related to the current research, remote haptic exploration of an inclined surface by way of a wielded rod has been shown to tap into equivalent information to that of vision, for the stand-on-ability of that surface (Fitzpatrick et al., 1994; Malek & Wagman, 2008; Regia-Corte & Wagman, 2008).

Recent research has brought the notion of equivalency into question. Hajnal, et al. (2016) have shown that vision is accurate and matches physical capabilities for standing on sloped surfaces, whereas haptic perception is more conservative, leading to
underestimation of stand-on-ability. When asked for such judgments while visually inspecting various inclinations, perceived maximal stand-on-able slopes align closely with physical action boundaries. When asked for such judgments while using haptic exploration of the surface (i.e., by taking a half-step onto an occluded sloped surface), perceptual responses significantly undershot the actual action boundary. This finding may be the result of inherent differences between the visual and haptic sensory systems with respect to the control of action. Alternatively, such differences may arise as a result of the differential suitability of each system for given tasks. Fitzpatrick et al. (1994) note that for certain tasks, such as identifying substance properties, haptics will be superior to vision; in other tasks, such as geographical slant perception, the two systems may in fact be identical.

The visual system tends to be prospective, planning actions and plotting courses for locomotion. The haptic system tends to be more immediate, carrying with its judgments behaviorally relevant consequences. That is to say, making conservative judgments based on haptic information generated at the ankle is beneficial in that underestimating physical capabilities will result in safer locomotion. The visual system has the luxury of making perceptual judgments about potential actions in the absence of immediate behavioral consequences. Thus, visually overestimating physical capabilities will not result in an injurious fall whereas making the same mistake using haptic information may well result in such a consequence. In this respect, the percepts generated using visual inspection when compared with those generated using haptic exploration are quite different: the haptic system may incorrectly inform the perceiver that a surface will not support upright standing when in reality it may; the visual system may correctly
inform the perceiver that the same surface will indeed support normal standing. With respect to an individual’s physical capabilities, the haptic system seems to employ an adaptive safety buffer, resulting in safer locomotion. Further evidence for this type of buffer can be seen when an individual ascends a staircase: each step carries with it a margin of error such that each footfall overshoots the vertical distance required to raise the foot and clear the stair’s riser (Riener, Rabuffetti, & Frigo, 2002). In theory, the individual should only raise the foot enough to clear the riser and no more. However, this is not how human stair-climbing behavior occurs. Each step employs a buffer, overshooting the required vertical distance, ensuring relatively safe ascension without much sacrifice to accuracy or metabolic costs (Proffitt, 2006).

Stoffregen and Bardy (2001) have also questioned the claim that perceptual systems such as vision and haptics should be equivalent. They proposed a global energy array that incorporates all task-relevant energy types as the singular array to which perceptual systems successfully respond. Experimental psychologists make a mistake when they test vision, haptics and other modalities in isolation (Hajnal et al., 2016). According to Stoffregen and Bardy, this mistake is the reason why visual and haptic perception appear to be different. When both are simultaneously sampling the global array, perception accurately corresponds to action capabilities. For example, when you feel and see where you are stepping at the same time, perceiving whether a surface can be stood on is easy and accurate. The global array contains accurate information for perception and, under this interpretation, all perception that occurs under natural circumstances is by definition multisensory. The present thesis makes a step in this direction: whereas Hajnal et al. (2016) tested vision and haptics in isolation, the current
experiment sets out to measure one modality using the other. Specifically, in one condition, haptic perception will be measured by visual estimation, and in another condition, visual perception will be measured by haptic estimation. The prediction is that if vision and haptics are truly equivalent, then measuring haptics with vision should produce the same percept as when measuring vision with haptics\(^1\).

Perceiving the Affordance of Stand-on-ability

Kinsella-Shaw et al. (1992) asked observers to provide judgments of walk-on-ability for a sloped surface in two manners: by instructing the researcher to adjust a visible slope to the maximal angle that will support walking and by haptically exploring a small occluded ramp and instructing the researcher to adjust the visible surface until the two are perceptually parallel. Across these experiments, the researchers found two notable results: (1) that observers are capable of perceiving maximal slopes that will support walking and (2) that observers are highly accurate in judging the walk-on-ability of extreme slopes (e.g., 10°, 15°, 40°, 50°, etc.). This latter point underscores the notion that perception of geographic slant is dependent on biomechanical constraints, i.e. observers are capable of perceiving slopes that will and will not support walking as long as they are very clearly shallow or steep. As the angle of inclination approaches the transition point (i.e., the point at which the surface no longer supports standing upright), affordance judgments become much more variable.

The experiment detailed below extends Kinsella-Shaw et al.’s paradigm (1992) to include comparisons among matches between both vision and haptics. Additional variables will also be employed to determine if perceptual accuracy can be predicted by
multi-scale interactions measured using the multifractal analysis of postural data (Ihlen, 2012).

Embodied Cognition and Multiscale Interactions in Vision and Haptics

According to the theory of embodied cognition (Chemero, 2009) bodily experiences and behavior are intrinsically linked to cognitive performance. One consequence of this assumption is that perception, an exemplary cognitive process, and action, an exemplary expression of behavioral activity, are integrated, and best understood as parts of the same organism-environment system.

A growing body of research suggests that the answers to many of the questions surrounding the sensory systems and their involvement in human perception and action might be revealed by considering multiscale interactions found in the organism-environment system (Palatinus, Kelty-Stephen, Kinsella-Shaw, Carello, & Turvey, 2014). The fluctuations that arise at different scales of the organism-environment system influence each other, and may be detected using multifractal detrended fluctuation analysis (MFDFA; Ihlen, 2012; Kantelhardt et al., 2002). These fluctuations may lend explanatory power to the apparent differences between vision and haptics, perhaps to the point of predicting perceptual responses. Consider the eye, which is seated within a head, which sits atop a body: each movement at each anatomical scale has a bidirectional effect on every other scale. For example, the body moves the head which moves the eye; eye movements inform head movements, which inform bodily movements; and so on (Palatinus, 2013). These interactions can be detected in the patterns of scale invariance of physiological and behavioral time series data (Peng, Havlin, Stanley, & Goldberger, 1995; Stephen & Hajnal, 2011; Seuront & Cribb, 2011).
Applying MFDFA to the time series data resulting from head displacements measured with motion capture equipment may allow predictions of affordance judgments. MFDFA is a spectral analysis method that computes the multifractal structure of variability at multiple scales. One can think of multifractality as a complex measure of spread, a distant “cousin” of standard deviation and variance. In the present case, data consisted of time series recordings of head displacements measured during the perceptual task of attending to the stimulus surface as the observer sampled environmental information to make a perceptual judgment.

Recent research has indicated that the width of the multifractal spectrum is the most relevant parameter that can be computed by MFDFA in perceptual tasks (Palatinus et al., 2014; Eddy & Kelty-Stephen, 2015). Multifractal spectrum width has been used to predict cognitive performance in decision making tasks (Anastas, Kelty-Stephen, & Dixon, 2014; Kelty-Stephen, Stirling, & Lipsitz, 2016), and a variety of perceptual tasks (Davis, Brooks, & Dixon, 2016; Eddy & Kelty-Stephen, 2015; Munafo, Curry, Wade, & Stoffregen, 2016). In the current study multifractal spectrum width was used to predict perceptual responses (yes/no affordance judgments), confidence judgments, and matching judgments. Other predictors included geographical slant angle of the stimulus surface and perceptual modality (haptic or visual).

It was hypothesized that all predictors would explain significant portions of the variance in affordance judgments, confidence judgments, and matching judgments. The proposal that measures of bodily movement could explain perceptual responses fits into the general framework of embodied cognition, which holds that bodily expressions of behavior (such as movement patterns in three-dimensional space) shape cognitive
processes (such as perception). It is also consistent with the specific assumption that perception and action are integrated processes (Gibson, 1966; 1979), so that action measurements reveal perceptual performance, and vice versa.
CHAPTER II - METHOD

Participants

Forty-four undergraduate students (28 women and 16 men) at the University of Southern Mississippi participated in this experiment in fulfillment of an extra credit option in their psychology courses. The average height of participants was 168.53 cm (SD = 10.75 cm). The average age was 21.27 years (SD = 3.60 years).

Materials and Apparatus

The apparatus consisted of two sturdy plywood surface ramps, one of which served as the visual stimulus and the other served as the haptic stimulus. The visual stimulus (152.40 cm long, 91.44 cm wide) was supported on one end by a metal crossbar that was held by several notches cut into two wooden support bars (153.67 cm tall). The wooden supports stood vertically on the left and right sides of a support frame that stabilized the entire apparatus. The height of the crossbar was changed from trial to trial by placing it into one of the nine pairs of notches cut into the support bars to create nine surface angles ranging from 12˚ to 48˚ in varying increments of 3˚ and 6˚ (see Figure 1 for details about the experimental setup). The ramp and the surroundings were covered with green carpet material of uniform texture.

The haptic stimulus (35.56 cm long, 30.48 cm wide) was attached at the near edge to a base of the same dimensions using a door hinge. A strip of Velcro was affixed to the top of the base so that wedges of varying size could be placed between the base and the ramp surface in order to create angles that correspond to the visual stimulus (Figure 1).

Participants stood on the floor of the laboratory 5 cm in front of the bottom edge of both ramp surfaces. A black felt curtain was placed in front of the participant covering
Figure 1. Apparatus and Experimental Conditions

(A) A black felt curtain is situated between the observer and the researcher to occlude the support frame, researcher, and surrounding surfaces. Visual-match condition: observers place a foot onto a small occluded ramp (placed inside a box indicated by grey rectangle) and instruct the researcher to adjust the large ramp until it is perceptually parallel with the smaller ramp being felt. Ramp angles denoted by \( \alpha \) and \( \beta \), respectively. Visible surface (highlighted in red) denoted by line segment CD. (B) A black felt curtain is situated between the observer and the researcher to occlude the support frame, researcher, and surrounding surfaces. Haptic-match condition: observers place a foot onto a small occluded ramp and instruct the researcher to make adjustments with a pulley until the small ramp is perceptually parallel with the larger ramp being viewed. Ramp angles denoted by \( \alpha \) and \( \beta \), respectively. Visible surface (highlighted in red) denoted by line segment CD.
the top 2/3 of the visual ramp area, occluding the far edge of the ramp, the crossbar, the 
two support bars, and one of the experimenters who stood behind the apparatus and set 
the angle of the ramp before and during each new trial. A second curtain was used in the 
visual-matching condition, which occluded the entire visual stimulus while the 
participant considered the haptic stimulus. A third curtain was used to fully occlude the 
haptic stimulus and another researcher who sat nearby making adjustments to that 
stimulus.

Infrared motion-tracking cameras and related software (Vicon, Nexus; Figure 2) 
were used to track head movements of participants. A small reflective marker was affixed 
to the back of the participant’s head using a cloth headband and the cameras were 
aranged behind the participant so that he or she would not be distracted and overt 
attention was directed toward the ramp stimulus. The cameras recorded fluctuations in 
the observer’s posture by tracking the marker in three-dimensional space.

Experimental Design

In a 2 (matching condition) × 9 (slope angle) mixed factorial design, participants 
provided affordance judgments, confidence ratings, and matching judgments 3 times for 
9 angle inclinations: 12, 18, 24, 27, 30, 33, 36, 42, and 48 degrees. These judgments were 
provided within 2 conditions: haptic-matching (visual presentation and haptic matching) 
and visual-matching (haptic presentation and visual matching). Condition was used as a 
between-subjects factor, meaning each participant was exposed only to a single 
condition. This resulted in 27 total experimental trials per session, excluding action 
capability measures and demographic/debriefing questionnaires. Each session was 
completed in less than an hour.
Figure 2. Vicon Motion Capture Cameras
Cameras emitted infrared light and tracked a reflective marker attached to a headband worn by the participant. Recordings were taken during the first 15 seconds of each experimental trial.

Procedure

Perceptual Task

After filling out the consent form and listening to a set of oral instructions, the participant was asked to stand in front of the ramp (Figure 1). In the haptic-matching condition, the participant looked at the visible portion of the ramp (bottom 1/3 of the surface area) and attempted to remain standing as still as possible for 15 seconds. During this interval, the motion-tracking cameras arranged behind the participant recorded
changes in head position in a three-dimensional coordinate system. The participant then reported (yes or no) whether he or she would be able to stand on the surface with both feet, without bending at the knees, the waist, or shifting their weight up to their toes (cf. Fitzpatrick, Carello, Schmidt, & Corey, 1994; Malek & Wagman, 2008).

After responding, participants were asked to rate the degree to which they are confident in their yes/no answer using a Likert scale ranging from 1 (not confident at all) to 7 (extremely confident). If clarity was needed, the researcher emphasized the meaning of the confidence rating between trials.

Finally, the participant was asked to haptically match the second ramp surface to the original visual surface inclination. The participant took a half step through the curtain and onto the fully occluded haptic stimulus while the researcher adjusted the surface inclination using a pulley and rope until the participant indicated that it was perceptually parallel to the visual stimulus. Participants were instructed to respond without overt thought or reflections. There were no explicit time constraints for responses on any given trial.

The visual-matching condition was identical to the haptic-matching condition with one exception: the participant took a half step onto the haptic stimulus, which was set to a discreet angle, then responded to the affordance and confidence questions, then attempted to match the visual stimulus to the haptic stimulus. Participants were neither encouraged nor discouraged to explore either stimulus by shifting their gaze or moving the foot after pedal contact. Participants did not receive feedback about the accuracy of their responses, nor were they allowed to attempt standing with both feet on either of the
stimuli. No measures were taken to prevent the participant from hearing background noises from the experimenters setting up each successive trial behind the curtains.

The ordering of haptic-matching and visual-matching conditions was counterbalanced across participants. Each angle was presented three times in each condition and the order in which surface angles were presented was randomized within each block. Thus, each participant completed a total of 27 trials (3 presentations of 9 angles). The sequence of stimulus presentation and the schedule of measurements is summarized in Table 1 for both experimental conditions.

**Behavioral Task**

After the perceptual task was completed, the larger ramp was set to the smallest surface angle setting (12º). The participant then attempted to stand on the ramp’s surface without bending at the knees, waist, or shifting his or her weight toward the toes⁴. If the participant was able to remain standing on the ramp for at least 5 seconds, then he or she stepped down and the surface was raised to the next steepest angle setting, and the participant repeated the task. The setting at which the participant was no longer able to stand for 5 seconds was recorded and the task was repeated 3 additional times in double-staircase fashion (Cornsweet, 1962) alternating in ascending and descending angle settings (i.e., beginning at 12º and increasing, or beginning at 48º and decreasing each trial). Angles at which the participant could no longer stand (ascending trials) and angles at which they could stand (descending trials) were averaged to obtain the individual’s action boundary, that is, the maximal geographic slant angle that affords upright stance.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Stimulus (head motion recorded for 15 seconds)</th>
<th>Response to presented stimulus</th>
<th>Matching response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual presentation, haptic matching</td>
<td>Observe large ramp surface</td>
<td>Visual Affordance judgment, confidence rating</td>
<td>Match visual stimulus by pedal adjustment of small ramp</td>
</tr>
<tr>
<td>Haptic presentation, visual matching</td>
<td>Place right foot on small ramp</td>
<td>Haptic Affordance judgment, confidence rating</td>
<td>Match felt stimulus by visual adjustment of large ramp</td>
</tr>
</tbody>
</table>
CHAPTER III - RESULTS

Perceptual Task

Probability Data

A 2 (Matching Condition) x 9 (Angle) mixed analysis of variance (ANOVA) revealed a main effect of Angle, $F(8, 336) = 145.56, p < .0001, \eta_p^2 = .776$, indicating that participants’ affordance judgments transitioned from “yes” to “no” as a function of increasing surface angles (Figure 3). However, neither the main effect of Matching Condition ($F(1, 336) = .183, p = .67, \eta_p^2 = .004$), nor the interaction ($F(8, 336) = .231, p = .99, \eta_p^2 = .005$) were significant.

Affordance Judgments

![Figure 3. Probability Data for Affordance Judgments](image)

Data shown as a function of geographical slant angle and matching condition showing the Angle x Matching condition interaction.

Error bars represent ±1 standard error of the mean.
Typically, binary data (e.g., yes/no affordance judgments) are not well suited for ANOVA as the assumptions of homoscedasticity and normality of error distributions is often violated. However, with equal group sizes and certain criteria having been met, the ANOVA is robust to such violations (Lunney, 1970). Nevertheless, a mixed effects hierarchical logistic regression (Bates, Mächler, Bolker, & Walker, 2015) was used to predict affordance judgments (see Model 1 in Table 2). The pattern of results partially overlapped those obtained by ANOVA: a main effect of angle was detected, $B = -0.547$, $SE = 0.062$, $p < .001$, indicating that participants’ affordance judgments transitioned from “yes” to “no” as a function of increasing surface angle. Contrary to the ANOVA, the main effect of Matching Condition ($B = -5.59$, $SE = 2.01$, $p < .006$), and the interaction ($B = 0.17$, $SE = 0.07$, $p < .01$) were both significant.

**Perceptual Boundaries (Individual Participant Data)**

At the level of individual participants, the perceptual boundary for each participant in a given condition was the steepest surface angle that received a yes response on at least half of the trials in that condition (i.e., on at least two of the three trials; cf. Malek & Wagman, 2008). The perceptual boundary in the haptic-match condition ($M = 30.27^\circ$, $SD = 6.14^\circ$) was not different from the perceptual boundary in the visual-match condition ($M = 29.86^\circ$, $SD = 5.11^\circ$; $t(42) = .240$, $p = .81$). The behavioral boundaries in the haptic match condition ($M = 32.39^\circ$, $SD = 4.77^\circ$) and the visual-match condition ($M = 30.97^\circ$, $SD = 3.61^\circ$) were not different from one another, $t(42) = 1.11$, $p = .27$, nor from their respective perceptual boundaries (haptic-match: $t(21) = 1.24$, $p = .23$; visual-match: $t(21) = .94$, $p = .36$).
Table 2

*Mixed Effects Hierarchical Logistic Regression on Affordance Judgments*

<table>
<thead>
<tr>
<th>Model</th>
<th>Predictors</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (base)</td>
<td>Angle*Condition</td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>Mean*Model 1</td>
<td>.318</td>
</tr>
<tr>
<td>1b</td>
<td>MFW*Model 1</td>
<td>.014</td>
</tr>
<tr>
<td>1c (full)</td>
<td>Model 1a + Model 1b</td>
<td>.018 (compared to Model 1a)</td>
</tr>
</tbody>
</table>

Note: the random effects consisted of random intercepts for participants, as well as by-participant random slopes for the effect of Angle.

*Perceptual Boundaries (Aggregate Data)*

Probit analysis (Finney, 1971) was used to generate perceptual boundaries in both conditions in aggregate. This boundary identifies the surface angle at which a “yes” response would be given on 50% of trials (cf. Fitzpatrick et al., 1994; Malek & Wagman, 2008). The perceptual boundary occurred at 32.11º (with lower and upper bounds on a 95% confidence interval of 30.46º and 33.83º, respectively) in the haptic-match condition, and at 31.09º (with lower and upper bounds on a 95% confidence interval of 30.15º and 32.05º, respectively) in the visual-match condition. The overlapping confidence intervals suggested that these values did not differ significantly.

*Two One-Sided Tests for Equivalence*

The reader may argue that the absence of differences, as has been reported so far, does not necessarily demonstrate equivalence between vision and haptics. To this end,
tests of equivalence (Walker & Nowacki, 2011), which are commonly used in the biomedical sciences to evaluate new drug treatments to ensure that one drug performs at least as well as its predecessor, were used to establish equivalence between perceptual and behavioral boundaries across conditions. These tests reverse the roles of traditional null and alternative hypotheses in statistical testing such that the null hypothesis states that there are differences between the hypothetical population parameters; the alternative hypothesis then becomes the statement that there are no differences between the parameters.

The most common method of testing for equivalence is the two one-sided test (TOST; Walker & Nowacki, 2011). This method utilizes two one-tailed $t$-tests which establish a critical region based upon some margin of change ($-\partial, \partial$) chosen by the researcher. If the obtained statistics of each test fall beyond the critical value, and in turn within the critical region, then the two groups are said to be equivalent. There appears to be little in the way of guidelines for choosing this margin of equivalence, however other investigations of geographic slant have chosen margins close to increments of change that are relevant to locomotion (e.g., ± 5º; Wagman & Hajnal, 2015). Such a margin is sensible for the current investigation, however, in an effort to provide an empirical justification for the margin, the overall error rate in matching judgments was calculated to establish the margin of equivalence. The thinking here is that if a participant considers a stimulus of 24º but sets the matching stimulus to 30º, in effect claiming that the two are equal (parallel), then this difference may fall below a just-noticeable threshold; it follows that the absolute value of the average error in matching judgments (haptic-match condition = 6.3º, visual-match condition = 6.4º) may constitute practical goalposts for the
margin of equivalence. Accordingly, the margin of equivalence was conservatively set to ± 6° for the TOSTs in this investigation.

Equivalence was found between: the perceptual boundary (M = 30.27°, SD = 6.13°) and the behavioral boundary (M = 32.39°, SD = 4.77°) in the haptic-match condition, $t_1(21) = -4.75$ and $t_2 (21) = 2.28$, $t_{crit} = ±1.72$; the perceptual boundary (M = 29.86°, SD = 5.24°) and the behavioral boundary (M = 30.97°, SD = 3.61°) in the visual-match condition, $t_1(21) = -6.01$ and $t_2 (21) = 4.13$, $t_{crit} = ±1.72$; the perceptual boundaries across conditions, $t_1(42) = -3.25$ and $t_2 (42) = 3.73$, $t_{crit} = ±1.68$; and the behavioral boundaries across conditions, $t_1(42) = -3.59$ and $t_2 (42) = 5.80$, $t_{crit} = ±1.68$.

**Signal Detection Data**

The mean frequency of hits (yes judgments to angles less than or equal to the behavioral boundary) and false alarms (yes judgments to angles greater than the behavioral boundary) were compared in each condition. For each participant in each condition, the total number of hits was divided by the number of trials for which the surface angle was less than or equal to the behavioral boundary, and the total number of false alarms was divided by the number of trials for which the angle was greater than the behavioral boundary. A t-test on (corrected) d’ values suggested that participants were equally able to differentiate surface angles that afford standing from those that do not in the haptic-match condition (M = 2.17, SD = 0.66) and in the visual-match condition (M = 2.08, SD = 0.41), $t(35.05) = .561$, $p = .579$.

**Confidence Data**

A 2 (Matching Condition) x 9 (Angle) mixed ANOVA revealed a main effect of Angle, $F(8, 336) = 33.61$, $p < .0001$, $\eta^2 = .444$, indicating that participants were more
certain about judgments made at extreme angles (e.g., 12º and 48º) than they were about judgments made at more ambiguous angles (i.e., angles near the behavioral boundary; Figure 4). Neither the main effect of Matching Condition, $F(1, 42) = 0.06, p = .82, \eta_p^2 = .001$, nor the interaction, $F(8, 336) = 0.85, p = .56, \eta_p^2 = .020$, were significant.

**Confidence Judgements**

![Confidence Judgements Graph](image)

*Figure 4. Confidence Data*

Data shown as a function Angle and Matching condition. Error bars represent ±1 standard error of the mean.

Participants were least confident ($M = 4.62, SD = 1.15$) when considering the stimulus at 30º and, relatedly, the average angle at which confidence was minimal occurred at 30.44º ($SD = 5.52º$). Follow-up *t*-tests showed that this angle was not significantly different from the haptic-match perceptual boundary, $t(21) = .94, p = .38$; the haptic-match behavioral boundary, $t(21) = -1.03, p = .32$; the visual-match perceptual boundary, $t(21) = .14, p = .89$; nor the visual-match behavioral boundary, $t(21) = -0.56, p = .58$. 

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Ordinal data, like binary data, are not well suited for ANOVA due to several violations of statistical assumptions. Accordingly, a mixed effects cumulative link model (Agresti, 2002) was used to predict confidence judgments (Model 2, Table 3). Evident in Figure 4, confidence was a curvilinear function of geographical slant angle, therefore we modeled it by adding the quadratic term of Angle to the list of predictors (Angle^2). The pattern of results in this case differed from the ANOVA: the main effect of Angle was not significant, $B = -0.012$, $SE = 0.011$, $p = 0.30$; neither the main effect of Matching Condition, $B = 0.231$, $SE = 0.285$, $p = .42$, nor the interaction, $B = 0.006$, $SE = 0.015$, $p = .71$. However, the main effect of Angle^2 was significant, $B = 0.018$, $SE = 0.002$, $p < .001$.

Table 3

<table>
<thead>
<tr>
<th>Model</th>
<th>Predictors</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (base)</td>
<td>Angle<em>Condition + Angle^2</em>Condition</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>Mean* Model 2</td>
<td>.318</td>
</tr>
<tr>
<td>2b</td>
<td>MFW*Model 2</td>
<td>.007</td>
</tr>
<tr>
<td>2c (full)</td>
<td>Model 2a + Model 2b</td>
<td>.020 (compared to Model 2a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.610 (compared to Model 2b)</td>
</tr>
</tbody>
</table>

Note: the random effects consisted of random intercepts for participants, as well as by-participant random slopes for the effect of Angle^2.
Matching Data

A 2 (Matching Condition) x 9 (Angle) mixed ANOVA revealed a main effect of Angle, \( F(8, 336) = 138.56, p < .0001, \eta^2_p = .767 \), indicating that participants’ matching judgments increased as a function of surface angle (Figure 5). The main effect of Matching Condition was also significant, \( F(1, 42) = 11.50, p < .002, \eta^2_p = .215 \). The interaction was not significant, \( F(8, 336) = 0.35, p = .95, \eta^2_p = .008 \).

In order to account for participants’ raw responses, a linear mixed effects model was used to predict matching judgments (Model 3, Table 4). The pattern of results was similar to the ANOVA: the main effect of angle was significant, \( B = 0.623, SE = 0.02, p < .001 \); the main effect of Matching Condition was also significant, \( B = -3.625, SE = 1.43, p < .015 \), such that haptic matching judgments were overall larger than visual matching judgments. The Angle x Condition interaction was not significant, \( B = 0.026, SE = 0.042, p = .54 \).

The linear regression equations in each condition (haptic-match, \( y=0.62x+13.0, r^2=0.99 \); visual-match, \( y=0.64x+9.61, r^2=0.99 \)) were nearly identical save for the intercept terms.

Motion Tracking Data

Vicon motion tracking cameras, set to a sampling rate of 200Hz, recorded the head displacements of each participant by tracking a reflective marker worn on the head for the first 15s of each trial. During this interval, participants were asked to consider one of the two stimuli (visual or haptic) while attempting to remain as still as possible. Each trial yielded 3,000 sets of x-y-z coordinates, which correspond to the reflective marker’s position in three-dimensional space during stimulus exposure. Each series of coordinates
Figure 5. Matching Data

Data shown as a function of Angle and Matching condition. Error bars represent ±1 standard error of the mean.

was segmented into three blocks spanning the first 50%, the second 50%, and then the middle 50% (which incorporated the latter half of Block 1 and the initial half of Block 3).

Magnitude changes in the coordinates were converted into time series appropriate for multifractal detrended fluctuation analysis (MFDFA; Ihlen, 2012). The MFDA calculates the set of scaling exponents that reflect long-term correlations in the structure of variability of the timeseries at multiple scales. The resulting output parameters were hypothesized to predict the dependent measures (i.e., affordance judgments, confidence ratings, and matching judgments) above and beyond traditional measures of central tendency (e.g., mean, standard error).
Table 4

*Linear Mixed Effects Model on Matching Judgments*

<table>
<thead>
<tr>
<th>Model</th>
<th>Predictors</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 (base)</td>
<td>Angle*Condition</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Mean*Model 3</td>
<td>.904</td>
</tr>
<tr>
<td>3b</td>
<td>MFW*Model 3</td>
<td>.447</td>
</tr>
<tr>
<td>3c (full)</td>
<td>Model 3a + Model 3b</td>
<td>.372 (compared to Model 3a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.811 (compared to Model 3b)</td>
</tr>
</tbody>
</table>

Note: the random effects consisted of random intercepts for participants, as well as by-participant random slopes for the effect of Angle.

*Probability Data*

Additional mixed effects hierarchical logistic regressions were used to predict affordance judgments (Table 2). Model 1 was updated with the output parameters derived from the MFDFA: mean, standard deviation, and multifractal spectrum width (MFW). Of these parameters, only the mean of Block 2 and the MFW of Block 2 contributed improvements to the original model, so all other blocks were dropped from the analyses reported below.

When included as a predictor variable, the mean head displacement did not improve Model 1 significantly, $X^2(4) = 4.72, p = .318$ (Model 1a). Model 1a revealed a negative main effect of Angle, $B = -0.54$, SE = 0.06, $p < .0001$, suggesting that the likelihood of ‘yes’ responses decreased as surface steepness increased; and a negative main effect of Matching Condition, $B = -5.50$, SE = 2.00, $p < .006$, suggesting that the
likelihood of ‘yes’ responses was lower in the visual-match condition. These main effects were superseded by a significant positive interaction between Angle and Matching Condition, $B = 0.16$, SE $= 0.07$, $p < .011$, and by a three-way interaction between Angle, Matching Condition, and Mean, $B = -.011$, SE $= 0.05$, $p < .04$ (Figure 6), suggesting that head movements significantly differentiated the pattern of affordance judgments as a function of slant angles and matching condition.

When included as a predictor variable, the MFW improved upon Model 1 significantly, $X^2(4) = 12.42$, $p = .014$ (Model 1b). The effects and interactions revealed by Model 1 remained significant in this iteration, with the estimates given by Model 1b following the same pattern as Model 1. The main effect of MFW was not significant ($p = .66$), nor any of the interactions, suggesting that the addition of MFW did not explicitly improve Model 1 through its effects and interactions as did the Mean, but rather implicitly, by reinforcing the effects of Angle and Matching Condition. Accordingly, the MFW appears to demonstrate that body movements modulate the visual and haptic modalities when judging stand-on-ability.

**Confidence Data**

Additional cumulative link models were used to predict confidence judgments, again with updated models that included the mean head displacement and MFW from Block 2 (Table 3). When included as a predictor variable, the mean head displacement did not improve upon Model 2, $X^2(6) = 7.03$, $p = .318$ (Model 2a). Model 2a preserved
Figure 6. Angle x Matching Condition x Mean Interaction (Probability Data)

Proportion of ‘YES’ responses reflecting a significant Matching Condition x Angle x Mean interaction. The data were separated into a LOW and HIGH Mean group (top and bottom panel, respectively) based on a median split of the scaled mean magnitude of head movements.
the significant positive main effect of \( \text{Angle}^2 \) \((p < .001)\), and revealed a positive main effect of Mean, \( B = 0.34, SE = 0.17, p < .05 \), suggesting that high magnitude of head movement resulted in larger confidence, and vice versa. No other effects or interactions were significant.

When included as a predictor variable, the MFW improved upon Model 2 significantly, \( X^2(6) = 17.58, p = .007 \) (Model 2b). The updated model preserved the significant main effect of \( \text{Angle}^2 \) \((p < .001)\), and revealed an Angle x Matching Condition x MFW positive interaction, \( B = 0.046, SE = 0.016, p = .005 \), suggesting that when multifractal spectrum width (MFW) is low, the pattern of differences between matching conditions across slant angles is more pronounced than when MFW is high (Figure 7). No other effects or interactions were significant.

Matching Data

Body movement parameters (Mean and MFW) did not affect the prediction of matching judgments above and beyond the geometric (Angle) and perceptual modality (Matching Condition) factors (Table 4). The mixed effects model essentially returned the same results as the ANOVA reported earlier.
Figure 7. Angle x Matching Condition x MFW Interaction (Confidence Data)

Confidence judgments as a function of Matching Condition across slant angles in the LOW MFW (top panel) and HIGH MFW (bottom panel) groups. The LOW and HIGH MFW groups were defined by a median split of the scaled multifractal spectrum width of head movements.
CHAPTER IV – DISCUSSION

The current experiment had two goals: 1) shore up evidence for the equivalence of perceptual systems (Gibson, 1966, 1979); and 2) demonstrate that perceptual equivalence is modulated by action-based variables – serving as proof of the embodied nature of cognition. We chose the affordance task of stand-on-ability representing one of the most basic behavioral functions that terrestrial creatures routinely perform. Past research (e.g. Fitzpatrick et al., 1994) has demonstrated that visual perception of stand-on-ability appears to be identical to haptic perception. Participants, regardless of condition, responded similarly when judging whether slopes of varying inclinations would support upright stance. Further, participants were least confident in their perception at the behavioral boundary (cf. Doyon et al., 2015), independent of condition. Our present results showed that visual and haptic perception of affordances are equivalent across many measures and across many statistical analyses. Some differences do exist, however, and are modulated by action measures of body posture, perhaps revealing the complex intertwining of perception and action, and thus in support of our second goal.

What Promotes Equivalence and What Does Not?

Everyday perception and action occurs in a context that demands simultaneous use of several perceptual systems in real time. Consider, for instance, the act of changing a light bulb embedded within a ceiling fixture (Doyon et al., 2015). To replace the light bulb, one must orient the body in accordance with the fixture and use implements such as a reaching device or a stepstool if the fixture is beyond one’s maximal reach; this task requires at least two systems, vision and haptics, with the former aiding in locating and orienting the body and the latter aiding in grasping, reaching, screwing, and maintaining
balance in the case of using a stepstool. Recently, Wagman, Caputo, and Stoffregen (2016) proposed a hierarchical organization of affordances, to which we are sensitive, that is implicated in such affordance tasks. For example, in order for a young child to perceive a tall bathroom sink as affording the brushing of teeth, the child must first perceive several subordinate affordances, e.g., the stepstool is reachable, moveable, stand-on-able; the brush and toothpaste are both reachable, graspable and squeeze-able; the faucet is reachable and the knobs are turn-able; and so on. Everyday tasks then, like the brushing of one’s teeth or replacing a light bulb, comprise several subordinate or nested affordances to be realized sequentially before the realization of the superordinate goal.

Accordingly, the researcher makes a mistake when studying affordances using unimodal tasks; this is the current explanation for the differences found by Hajnal, Wagman, Doyon, and Clark (2016). Empirical results from such highly controlled and isolated laboratory tasks would lead one to believe that perceptual systems are indeed not equivalent. The issue is further complicated by the fact that certain tasks are more suitable for some perceptual systems, but not others. Fitzpatrick et al. (1994) noted that judging length is best when using vision and that judgments of substance are best when using haptic exploration. Similarly, vision and haptics have differential levels of experience in locomotion; visual perception is prospective, determining a surface’s walk-on-ability from a distance, without immediate behavioral consequences; haptic perception determines the walk-on-ability of a surface in the moment, carrying with it the potential for injury. The differences found by Hajnal et al. (2016) are reflective of these differential levels of experience revealed by the unimodal nature of the task. In contrast, the
multisensory nature of the current experiment promotes equivalence by requiring the participant to use both vision and haptics throughout each trial.

In the same vein, the researcher makes a mistake when forcing the participant to direct full attention to the affordance task. Everyday perception and action is largely automatic, independent of analytic processing (Heft, 1993). In the same way a basketball player may overthink a free throw, resulting in a missed basket, the participant may be overthinking the affordance task resulting in errors (Hajnal et al., 2016). The stand-on-ability of a surface is rarely, if ever, the focus of attention in everyday locomotion, yet the nature of the affordance task requires that the participant focus attention toward the question of what is stand-on-able, effectively dragging the automatic into the analytical realm. Heft (1993) found that participants were more accurate in a reaching task when it was embedded within the context of a larger cognitive task; in this respect, attention was diverted away from the presumably automatic action, resulting in less analytic processing and higher accuracy. Doyon et al. (2015) extended this idea by embedding a stand-on-ability task within a superordinate reaching task. Results mirrored Heft (1993) in that participants were more accurate in the stand-on-ability task when it was couched within the larger reaching task. Similarly, Keizer, De Brujin, Smeets, Dijkerman, and Postma (2013) found that participants were more accurate and more efficient when judging the pass-through-ability of apertures when participants were distracted by a secondary memory task. Such tasks, again, effectively divert attention away from the presumably automatic affordance judgments, resulting in improved accuracy. This issue of attention, like that of the unimodal nature of other affordance tasks, highlights the artificial
constraints introduced by the laboratory study of everyday perception and action, which reveal nonequivalence.

Calibration Differences in Vision and Haptics

The results of the current experiment may appear to be a uniform wall of null results. However, differences were observed across conditions where participants made matching judgments. The difference between matching judgments made in the haptic-match condition and the judgments made in the visual match condition corresponded to a constant offset of about 3 degrees. Since there was no Angle x Matching condition interaction for perceptual matches, this finding reflects a difference in calibration, not a difference in scaling, of the two perceptual systems. Like the differences found by Hajnal et al. (2016), this calibration offset is likely a product of the differential experience in judging stand-on-ability using vision and haptics. Alternatively, such an offset may be reflective of an adaptive safety buffer employed by the haptic system to ensure safe locomotion (cf. average of 10 cm vertical clearance of obstacles on the ground, see Patla, & Rietdyk, 1993). For a person to behave in a perfectly efficient manner, minimizing the metabolic cost of action (Proffitt, 2006) as much as possible, the person would lift the foot only so far as to clear the stair riser’s height, and no more. In this way, the least amount of energetic resources is consumed, and the individual is still successfully climbing stairs. This is not how we climb stairs, however; each footfall carries a margin of error, or an overshooting of the necessary height to successfully clear the riser. The consequence is a buffer by which the haptic system ensures safe locomotion over ambiguous or out-of-sight terrain.
Additionally, the current experiment’s task included an asymmetry in postural constraints (one-footed balancing in haptic condition versus two-footed stance in visual condition), and the nature of perceptual inputs and outputs (Figure 8). In the haptic-match condition, the participant is required to perceive the larger ramp’s surface visually (input), then perceive the smaller ramp’s surface haptically (input), then produce a haptic response (output) by instructing the researcher to stop the smaller ramp’s adjustment when the foot’s geometric configuration indicates the smaller ramp is parallel to the larger ramp. In the visual-match condition, the participant is required to perceive the smaller ramp haptically (input), then perceive the larger ramp visually (input), then produce a visual response (output) by instructing the researcher to stop the larger ramp’s adjustment when the visual information indicates the larger ramp is parallel to the smaller ramp.

Thus, the asymmetry is revealed in the number and nature of inputs and outputs for each system across conditions. Further, the demands placed upon each system by everyday locomotion are asymmetrical. Vision is a distance sense, acting prospectively, further removed from action than the haptic system; conversely, the haptic system is intertwined with action, perceiving in the moment and carrying potentially severe consequences (e.g., injury or death). However, whether this asymmetry explains the presence of a calibration offset, or the emergence of a mechanism for safe locomotion is speculative and requires further investigation.

Multiscale Interactions in Affordance Perception

The current experiment has also demonstrated that multiscale interactions can not only be detected in the movement patterns of participants, but also that these interactions can be
informative of perceptual performance. Specifically, we used multifractal spectrum width as a variable that describes the complexity of multiscale interactions to predict perceptual responses (affordance judgments and matching judgments) and cognitive responses (confidence judgments).

The notion that multiscale interactions are present in perception-action systems is rooted in Gottlieb’s (2007) probabilistic epigenesis framework, which states that bidirectional influences at multiple scales are lawful and measurements made at any scale should be reflective of interactions at other scales. For the purposes of the current research, remember that the eyes are seated in a head, which sits atop a body, which is embedded within an environment; movements of the eyes affect (and inform) movements of the head, which in turn affect movements of the body, which in turn affect variables in the environment.

Similarly, variables in the environment affect movements of the body, which affect movements of the head, and so on. Variability that emerges at any one of these scales cascades throughout the entire system, and as a result, measurement at any of these scales should be reflective of the variability emerging at another scale. For these reasons, the researcher should not neglect the contributions of action measures to the prediction of perceptual performance reported here. Accordingly, further inspection of the results calls for a more detailed and nuanced consideration of the multifractal analyses.

In the next sections we assessed the predictive power of various action measures extracted from postural sway (mean magnitude and multifractal spectrum width) for all the dependent variables that were collected.
Figure 8. Asymmetry of Perceptual Inputs and Outputs

(A) Visual-Match condition, (B) Haptic-Match conditions
**Probability Data**

The significant main effect of Matching Condition revealed that the likelihood of ‘yes’ answers was overall higher in the haptic match (visual stimulus) condition. This was qualified by the significant Matching condition x Angle interaction showing that the differences between modalities diminished with increased steepness of the stimulus. The negative Matching condition x Angle x Mean interaction (Figure 6) revealed two additional facts: 1) trials with larger magnitude of postural sway resulted in smaller probability of ‘yes’ answers around 30 degrees (near the behavioral boundary) in the haptic match condition as compared to the visual match condition; 2) the haptic match condition benefited the most from larger movements for angles beyond the behavioral boundary, but also from smaller movements at angles below the behavioral boundary. In all other ranges of angles and magnitudes of movement there were no differences between modalities.

Our conjecture was that increased head movement magnitude allows more exploration and gathering of more information (Gibson, 1979; Michaels & Carello, 1981). However, the exact reasons why larger head movements inflated affordance judgments in the visual stimulus condition beyond the behavioral boundary, whereas smaller movements facilitated affordance judgments in the visual stimulus condition below the behavioral boundary remains unclear. Future research is needed to uncover the exact connections among exploration magnitude, information detection, and accuracy.

It is interesting to note that while the addition of the Mean as a predictor did not significantly improve the overall predictive power of the regression models, the explicit interactions among spatial factors (angle), modalities (matching condition), and action
(mean magnitude of head sway) in Model 1a still modulated the prediction of perceptual responses. The deeper structure of head sway variability (MFW) has exerted its influence in a subtler manner: no explicit interactions involving multifractal spectrum width were found in Model 1b, however the inclusion of MFW has significantly improved the predictive power of Model 1.

Which action-based measure (Mean or MFW) was a better predictor of affordance judgments? In order to evaluate the unique contributions of Mean and MFW, we conducted a sequential multiple regression analysis (Table 2). When including the MFW into the model that already contained the Mean head displacement, the model was improved significantly, $X^2(4) = 11.96, p = .02$ (Model 1a compared to Model 1c). When including the Mean head displacement into the model that already contained the MFW, the model was not improved significantly, $X^2(4) = 4.26, p = .37$ (Model 1b compared to Model 1c). This indicated that MFW carved out unique variance not explained by Mean when predicting affordance judgments. The full logistic regression (Model 1c), which contained Angle, Matching Condition, Mean head displacement, and MFW preserved the same pattern of results as the scarcer Model 1b that contained MFW, but not Mean. In summary, MFW is a more valuable predictor of perceptual judgments than Mean head displacement. This suggests that the raw magnitude of head movements is not sufficient to explain perception of affordances, thus necessitating the consideration of multiscale interactions among perception and action measures.

Confidence Data

The results of the mixed models used for predicting confidence judgments followed the same pattern as the affordance judgment models: adding Mean to Model 2
did not explain additional variance, whereas adding MFW did. Specifically, the significant positive three-way Matching condition x Angle^2 x MFW interaction (Figure 7) has revealed that the degree of multifractality of head movements modulated confidence judgments up and down in different ways for angles below and above the behavioral boundary. In particular, trials with a large MFW (bottom panel of Figure 7) resulted in shifting up the angle associated with minimal confidence from 30 to 33 degrees in both matching conditions. As shown in the top panel of Figure 7, in trials with low multifractality of head movements confidence judgments were more separated between haptic and visual matching conditions, with the haptic matching condition resulting in larger and lower confidence above and below the behavioral boundary, respectively. No such modality differences were apparent for trials with a large multifractal spectrum width. As with affordance judgments, this indicates that multifractality, or more generally the complexity of head movements during the stimulus intake phase effectively influenced confidence judgments.

Similar to the sequential multiple regression analysis of affordance judgments, we created a comprehensive cumulative link model (Table 3, Model 2c) that contained the original Model 2 and both the Mean and MFW. When including the MFW into the model that already contained the Mean head displacement, the model was improved significantly, $X^2(6) = 15.04, p = .02$ (Model 2a compared to Model 2c). When including the Mean head displacement into the model that already contained the MFW, the model was not improved significantly, $X^2(6) = 4.50, p = .61$ (Model 2b compared to Model 2c). This indicated that MFW carved out unique variance not explained by Mean when predicting confidence judgments.
The full cumulative link model (Model 2c), which contained Angle, Matching Condition, Mean head displacement, and MFW mirrored the effects and interactions of the scarcer model that contained MFW (Model 2b), but not Mean. That the interactions with MFW remained significant across hierarchical models suggests that the MFW is a better predictor of confidence and underscores the notion that evaluative processes involved in assessing perception of affordances are modulated by the complex structure of variability (MFW), and not simply the raw magnitude of bodily movements (Mean).

**Matching Data**

Curiously, the movement parameters generated by the MF DMA did not aid the prediction of matching judgments (see Table 4 for details). The absence of effects of body movement parameters is likely due to the temporal positioning of the judgment relative to the recording of the movements. That is to say, the matching judgment was third (and final) in the sequence of responses and, as a result, the furthest removed response from the movement recordings. If the effects of movement persist beyond the time window of motion capture recording used in this study, then it is likely that they decayed by the time the participant made the matching judgment. Even if the effects of movement could persist throughout all responses, the matching response has no direct relevance to meaningful action, i.e., to the affordance of stand-on-ability.

**Limitations and Future Directions**

It is worth mentioning that the current experiment differs from other studies in the amount of stimulus exposure each participant experienced. Here, the participants were required to consider the stimulus for 15 seconds. This requirement presumably allowed the participant to gather more information for the task than participants in other studies,
which required participants to respond quickly (Heft, 1993) or to respond without temporal constraints (Doyon et al., 2015; Hajnal et al. 2016). The amount of stimulus exposure necessary to promote equivalence is still an open question, requiring further investigation.

The current experiment also failed to account for the consequences of action. In everyday locomotion, there exist real, potentially severe consequences for perceptual errors and clumsy steps. Participants in this case had no reasons to expect any real consequence for a given judgment. We expect that participants’ judgments may be contaminated to some extent by this absence of consequence; at the very least, this absence is another example of the artificial constraints introduced in the laboratory setting. The case may be that the consequences of action are among the critical variables influencing the realization of affordances. Future research is planned to test how real consequences of actions shape visual and haptic perception.

Conclusions

Ultimately, the current experiment demonstrates that environmental information may not be dependent on one perceptual modality alone. Rather, each sensory system might sample from a single global array (Stoffregen & Bardy, 2001), which contains all the behaviorally relevant information for a given task. Further, human sensory systems may be considered smart perceptual devices (Runeson, 1977), which specifically exploit information contained in the global array allowing amodal perception. In this respect, regardless of the sensory channel used, perception is in service of the same behavioral goal: an affordance that must be realized.
Since analyses of some dependent measures revealed differences between modalities it would perhaps behoove us to soften the demands for equivalence as required by Gibson’s (1966) theory of perception. Thus, recasting equivalence among sensory systems as correspondence of perceptual modalities through modulation by action measures is perhaps a more fruitful and empirically more realistic approach. The mechanisms underlying the correspondence between perceptual systems, action systems, and environmental constraints are still unknown.

In addition to Gottlieb’s probabilistic epigenesis framework a more recent neuroanatomical structural model of perceptual systems called tensegrity (Turvey & Fonseca, 2014) may offer inroads into describing the nature of perceptuomotor mechanisms at multiple scales. Tensegrity of the haptic system might be the underlying neuroanatomical mechanism governing haptic exploration, information detection, and perception, whereas the pattern of eye, head, and torso movements may govern visual perception in complementary ways.

While equivalence is at the heart of answering the title question “Do hills look as steep as they feel?” perhaps a more intriguing question is “For what behavioral purpose?”. Considering the contribution of action measures such as subtle head sway in perceptual tasks may provide us with the answer.
The most natural and ecologically valid condition would be to stimulate both the vision and haptic system simultaneously, as in everyday walking when we see where we are stepping while getting haptic feedback from our feet. However, past pilot data suggested that this leads to trivially accurate perception with very little variability. The current experiment is more conducive to statistical comparisons, and exercises better control over how long each sensory system is exposed to stimulation and how much each sense contributes to perception.

Participants were asked to rate the certainty, not the accuracy of their responses. To avoid conflating the two types of responses, the definition of confidence ratings was reiterated as needed during the experiment, while being careful to avoid biasing participant responses.

Realizing that the ramp is too small to support standing in reality may bias the judgment. However, participants were encouraged to imagine an extended foot ramp thus helping to minimize such confound.

Testing action boundaries might be affected by having both vision and haptics available during the action boundary assessment trials while all perceptual trials were limited to one modality or the other (Doyon, et al., 2015). This issue was addressed in a control pilot study where no differences were found in testing action boundaries when limited to vision or to haptics only.

We chose to only include parameters from Block 2 due to the nature of the task and the length of the recording. Variability in Block 1 may be the result of the participant settling into or orienting to the task; variability in Block 3 may be the result of fatigue or
boredom. While affordance judgments are often made nearly instantly, we presume the judgment is likely made after some orientation, but before any fatigue.

6Whether the realization of these hierarchically nested affordances is serial or parallel is still an open question. Further research is needed.

7The reader may ask if the repeated finding of null results is merely due to a lack of experimental power. To sate the reader, a post hoc power analysis was conducted using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) to determine the observed power. The observed power was found to be $\beta = .794$ indicating the experiment was sufficiently powered to find effects, if any exist.
APPENDIX B – IRB Approval Letter

NOTICE OF COMMITTEE ACTION

The project has been reviewed by The University of Southern Mississippi Institutional Review Board in accordance with Federal Drug Administration regulations (21 CFR 21, 111), Department of Health and Human Services (45 CFR Part 46), and university guidelines to ensure adherence to the following criteria:

- The risks to subjects are minimized.
- The risks to subjects are reasonable in relation to the anticipated benefits.
- The selection of subjects is equitable.
- Informed consent is adequate and appropriately documented.
- Where appropriate, the research plan makes adequate provisions for monitoring the data collected to ensure the safety of the subjects.
- Where appropriate, there are adequate provisions to protect the privacy of subjects and to maintain the confidentiality of all data.
- Appropriate additional safeguards have been included to protect vulnerable subjects.
- Any unanticipated, serious, or continuing problems encountered regarding risks to subjects must be reported immediately, but not later than 10 days following the event. This should be reported to the IRB Office via the "Adverse Effect Report Form".
- If approved, the maximum period of approval is limited to twelve months.
  Projects that exceed this period must submit an application for renewal or continuation.

PROTOCOL NUMBER: 15051802
PROJECT TITLE: Correspondence between Haptic and Visual Perception of Geographic Slant Do Hills Look as Steep as they Feel?
PROJECT TYPE: New Project
RESEARCHER(S): Jonathan K. Doyon
COLLEGE/DIVISION: College of Education and Psychology
DEPARTMENT: Experimental Psychology
FUNDING AGENCY/SPONSOR: NIA
IRB COMMITTEE ACTION: Expedited Review Approval
PERIOD OF APPROVAL: 06/05/2015 to 06/04/2016
Lawrence A. Hosman, Ph.D.
Institutional Review Board
REFERENCES


Doyon, J. K., Hajnal, A., Wagman, J. B., McGathy, M., Clark, J. D., & Palatinus, Z. (2015, March). Are we overthinking it? Haptic perception of geographic slant is accurate when embedded within a secondary task. *Susan A. Siltanen Graduate Student Research Symposium*. Symposium conducted at the meeting of the University of Southern Mississippi Graduate School, Hattiesburg, MS.


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