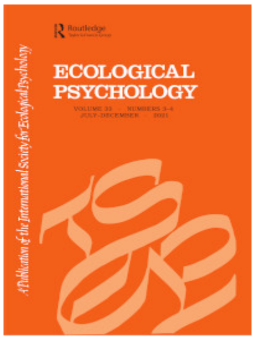

Ecological Psychology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/heco20

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ECOLOGICAL PSYCHOLOGY
https://doi.org/10.1080/10407413.2022.2035225

REPORT

Complex Postural Sway is Related to Perception of Stand-on-Ability

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ABSTRACT
Body movements during perceptual tasks can be considered as exploratory activity that facilitate perception. In the present study we tested whether the complexity of postural sway is related to perception of affordances. Effort-to-compress (ETC), a novel measure of complexity, was shown to be related to perception as compared to gross measures of body sway (mean magnitude and variability). Specifically, complexity was related to perceptual responses in a behavioral task (judge "standonableness" of sloped terrain), but not when numerical angle judgments of slope were solicited. Furthermore, ETC was extreme at the action boundary of standonableness whereas magnitude and variability of body sway were not. This provides further evidence that the purpose of perception is to guide meaningful behavior (perceive affordances) via active exploration, and not to estimate abstract numerical quantities such as slope angles of ramps. We concluded that moving the body in ways that produces complex exploratory activity is necessary to perceive affordances.

According to Gibson (1966) perception is an active process that unfolds through exploratory activities of the perceptual system, and performatory activities of the action system to produce behaviors. Postural sway is one example of an exploratory activity. Movements of the body while observing the world around us generate optic flow and gravitoinertial patterns of change of tension in the muscles, tendons, joints and the skin. Perception in behaviorally relevant tasks is specific to these patterns that serve as information. In contrast, mainstream perception science has traditionally assumed perception and action as separate and independent processes (Witt, 2018). The ecological approach claims that perception is an active and selective process of scanning (see Chapter 12 of Gibson, 1966) that engages in continuous movements of the eyes, head, torso, and the whole body in order to explore the environment (Van Andel et al., 2019). In the present study we investigated whether

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exploratory activity is related to perceptual responses in a goal directed task. Affordance tasks are well suited for this purpose, as they are set up to test perception of whether a particular action can be performed or not given a spatial layout of the environment. We chose the affordance task of perceiving whether a sloped surface can support upright stance because postural sway should be directly related to perception of stand-on-ability.

Linking perception and action

Early studies of affordances focused on discovering the scaling of task parameters to relevant body parts (i.e. riser height and leg length, respectively) that map onto perceptual responses in a one-to-one fashion (Warren, 1984). More recent studies have started measuring body movements during exploratory activity and hypothesized that the exploratory movements should be related to perceptual responses (Doyon et al., 2019, 2021; Hajnal et al., 2018; Masoner et al., 2020). The current study was designed to provide further support for this hypothesis.

Overview of the current study

The current study was modeled after the experimental design used in Hajnal et al. (2014) in which postural sway was measured as observers faced large ramps at different geographical slant angles in front of them[1]. Results showed that the complexity of postural sway changed as a function of changing the ramp angle, but in the absence of a behavioral task (other than standing upright) it was not clear what the exact role of postural sway was. Postural sway can be considered a form of exploratory activity, which is necessary for efficacious perception (Mark et al., 1990; Stoffregen et al., 2005). Nowhere does postural sway more directly assume the role of exploratory activity as during quiet standing to maintain upright balance and prevent falling, or to perceive properties of objects attached to the body (such as the length of skis carried on the back). A singular study by Palatinus et al. (2014) demonstrated that there is a direct link between exploratory activity performed via postural sway of the whole body in a dynamic touch task of perceiving length of unseen objects attached to one's torso. The overall motivation of the current study was to elaborate on the results of Hajnal et al. by introducing a behaviorally relevant, goal-oriented task, and to test if exploratory activity generated by postural sway is related to perception of potential actions. Two general hypotheses were posited: (1) complex descriptors of postural sway (effort to compress, or ETC; Nagaraj & Balasubramanian, 2017a, 2017b; see Method section for definition), not mean magnitude and variability of sway, should be related to perceptual responses, based on the growing empirical evidence that postural control is best characterized by complex measures of body movements (Masoner et al., 2020; Zhou et al., 2017); and (2) complex descriptors of postural sway should be related to

[1]The original motivation for the present study was to serve as a follow-up to Hajnal et al. (2014) where it was not clear if the effects on postural sway were due to ramp angles, the average eye-to-ramp surface distances, or both. The current study's experimental design and statistical analyses contained Angle × Distance interaction terms, which were implicitly incorporated into Hypothesis 2 (see text for details).

perceptual responses in functional (i.e. affordance) tasks, as opposed to nonfunctional (angle estimation) tasks, because one of the roles of postural control may be to guide goal-oriented actions via perception-action coupling (Mantel et al., 2015; Warren, 1990). In particular, we hypothesized that the effects of spatial variables (distance and slant) on variables describing sway (magnitude, variability, complexity) will be most pronounced at task-relevant slope angles. The task-relevant angle for the affordance task corresponds to the action boundary, typically around 30° (Hajnal et al., 2016; Malek & Wagman, 2008), whereas in the numeric angle estimation task it is at the midpoint of the range, typically around 45° (Durgin et al., 2010). The latter might be an example of a generic cognitive bias called anchoring (Tversky & Kahneman, 1974). The two hypotheses were tested on all measures of postural sway (mean magnitude, coefficient of variation, and ETC of head sway). Specifically, we hypothesized that complexity (as measured by ETC) should be the best moderator of perceptual responses (Hypothesis 1), but only in the affordance task (Hypothesis 2). This hypothesis is consistent with the ecological approach whose basic tenet is that perception and action are co-implicative in the guidance of goal-oriented behavior (Michaels & Carello, 1981, pp. 47–54).

Method

Participants

34 students (10 males) from a large public university in the Southeastern United States participated. The mean age was 19 years old. Participants were required to have normal or corrected-to-normal vision. In order to ensure the virtual reality (VR) system was calibrated correctly for each participant's body proportions eye height, shoulder height, and arm length measurements were taken. Due to equipment malfunction measurements were not recorded for one participant whose data was not included in subsequent statistical analyses. The mean eye height was 1.58 m (SD = 0.07m), the mean shoulder height was 1.42 m (SD = 0.06m), and the mean arm length was 0.58 m (SD = 0.06m). Participants were recruited through the Psychology Department's SONA Research Participation system for extra credit in their psychology courses.

Apparatus

The experiment was designed and displayed in the Unity game engine software (v2017.1.1fl) running on Windows 10 and used C# programing language to script events and commands. The virtual reality system was an Oculus Rift head mounted display and two controllers for making responses. The virtual environment presented ramps, at varying angles, covered in a green grass-like texture and were located on the floor in a large gray room either 0.2 m, 1.0 m or 3.0 m away from the participant's feet.

Design

Independent measures were ramp distance (near, mid, far) and angle (0° to 90° in 15° increments)[2]. We employed a 3 Distance (near, mid, far) × 7 Angle factorial experimental design. Dependent measures were yes/no responses about stand-on-ability in the affordance task, angle judgements in the angle task, and head movement parameters (mean magnitude, coefficient of variation, ETC) computed from recordings by the VR head mounted display as spatial coordinates of head motion (x, y and z coordinates in meters). The head position data were captured at a sampling rate of 50 Hz. From these coordinates, we computed the Euclidean distances between each adjacent sample of recording of the head position and generated a one-dimensional time series for each trial. These time series were analyzed in several ways. The overall mean was calculated to indicate the average magnitude of head movement. The coefficient of variation (CV) was computed by dividing each time series' standard deviation with the mean magnitude.

Effort-to-compress (Nagaraj & Balasubramanian, 2017a, 2017b) was chosen as the appropriate measure of complexity due to its suitability to handle short time series in a variety of fields, such as neuroscience (e.g., heart rate, Srilakshmi et al., 2018), ecological psychology (Masoner et al., 2020), and engineering (e.g., structural complexity of materials, Virmani & Nagaraj, 2019). ETC is a measure of the heterogeneity of the time series and the ease with which it can be converted into a homogeneous series. ETC measures heterogeneity by identifying "streaks" in the time series. These repeated occurrences (streaks or patterns) are labeled as a unit, effectively shortening the time series. This logic is also used in engineering technology and computer science to compress data files such as music files and digital images. The number of steps involved in compressing the time series into its smallest possible length is a measure of how complex the original series was. Specifically, signals requiring a large number of steps to homogenize the time series are considered more complex than signals requiring fewer steps. In the present experiment we used ETC as a measure of complexity of head movements by analyzing the Euclidean distance series for each trial.

Data analysis

Data were analyzed in R statistical package using a mixed-effects hierarchical logistic regression (using the *glmer* function from the *lme4* R package) on affordance judgments to test Hypothesis 1. Logistic regression is a more appropriate analysis than analysis of variance (ANOVA) because the dependent variable of affordance judgments is dichotomous (yes/no responses). The following model was used:

$$\begin{aligned}\text{Affordance Response} \sim\ & (\text{Trial}|\text{Participant}) + \text{Trial} + \text{Distance} \times \text{Angle} \times \text{Mean} \\ & + \text{Distance} \times \text{Angle} \times \text{CV} + \text{Distance} \times \text{Angle} \times \text{ETC}\end{aligned}$$

[2]In order to replicate the design of Hajnal et al. (2014) we used the same seven ramp angles and the near distance of 0.2m for ramp placement. The mid-range (1m) and far (3m) distance was added in order to represent a range within which most human activity takes place. This loosely resembles the division of space into personal (up to 2m), action (2–30m) and vista space (beyond 30m) by Cutting and Vishton (1995).

Trial and participant were set as random effects; all other variables were fixed effects. The model was built to test how affordance responses were affected by distance and angle. In addition, the model tested the moderating effects of mean magnitude (Mean), variability (CV), and complexity (ETC) as various measures of head movement. Since feedback was not provided, our emphasis was not to determine whether complexity is better or worse for predicting the accuracy of perceptual judgments. Instead, the regression analyses answered the question about which factor (ETC, CV, magnitude) explains a statistically significant portion of variance in perceptual judgments. All three movement parameters were normalized by subtracting the mean and converting the values into z-scores.

Angle judgements were analyzed using a linear mixed-effects model (employing the *lme* function from the *nlme* R package). The model was built using the same combination of factors as the logistic model:

$$\begin{aligned}\text{Angle Judgment} \sim \ & (\text{Trial}|\text{Participant}) + \text{Trial} + \text{Distance} \times \text{Angle} \times \text{Mean} \\ & + \text{Distance} \times \text{Angle} \times \text{CV} + \text{Distance} \times \text{Angle} \times \text{ETC}\end{aligned}$$

To test Hypothesis 1 multiple regression models were the optimal choice of statistical analyses due to the fact that the postural sway descriptors are continuous variables, and the spatial configuration variables are categorical. Additionally, linear mixed effects models have the advantage of working with fewer statistical assumptions (variables do not have to be normally distributed, homogeneity of variance is not required) than an ANOVA, tolerating missing data, and using raw data instead of averages over repetitions.

Just like with affordance judgements, we expected Mean, CV, and ETC to be influenced by the spatial configuration of the stimuli. Therefore, several 3 (Distance) $\times$ 7 (Angle) repeated-measures ANOVAs were conducted on Mean, CV, and ETC for the affordance task and the angle estimation task.

Procedure

After signing the consent form, participant's eye height, shoulder height, and arm length were measured. The participant donned the VR head mounted display and was handed two controllers. Participants were instructed to stand still facing the VR tracking sensors with the controllers held down by their side. The participants were notified that if at any time they experience strain or dizziness, they could take a break or discontinue participation without loss of incentives.

The study consisted of two conditions, the affordance task and the angle judgment task, each with 70 trials (including 7 practice trials at the beginning). The conditions were counterbalanced and each participant was run through both conditions. During each trial a virtual ramp was presented randomly at varying angles between 0° and 90° and at either near (0.2 m from the feet of the observer), mid-range (1 m away), or a far distance (3 m away; see Figure 1 for a graphic illustration of the trial structure). The ramps were presented in the same random order for both tasks.

During the affordance task the ramp was presented in the virtual environment and the participant was tasked with deciding whether or not they could stand upright with their feet flat on the ramp and their arms down to their side. The participant used the

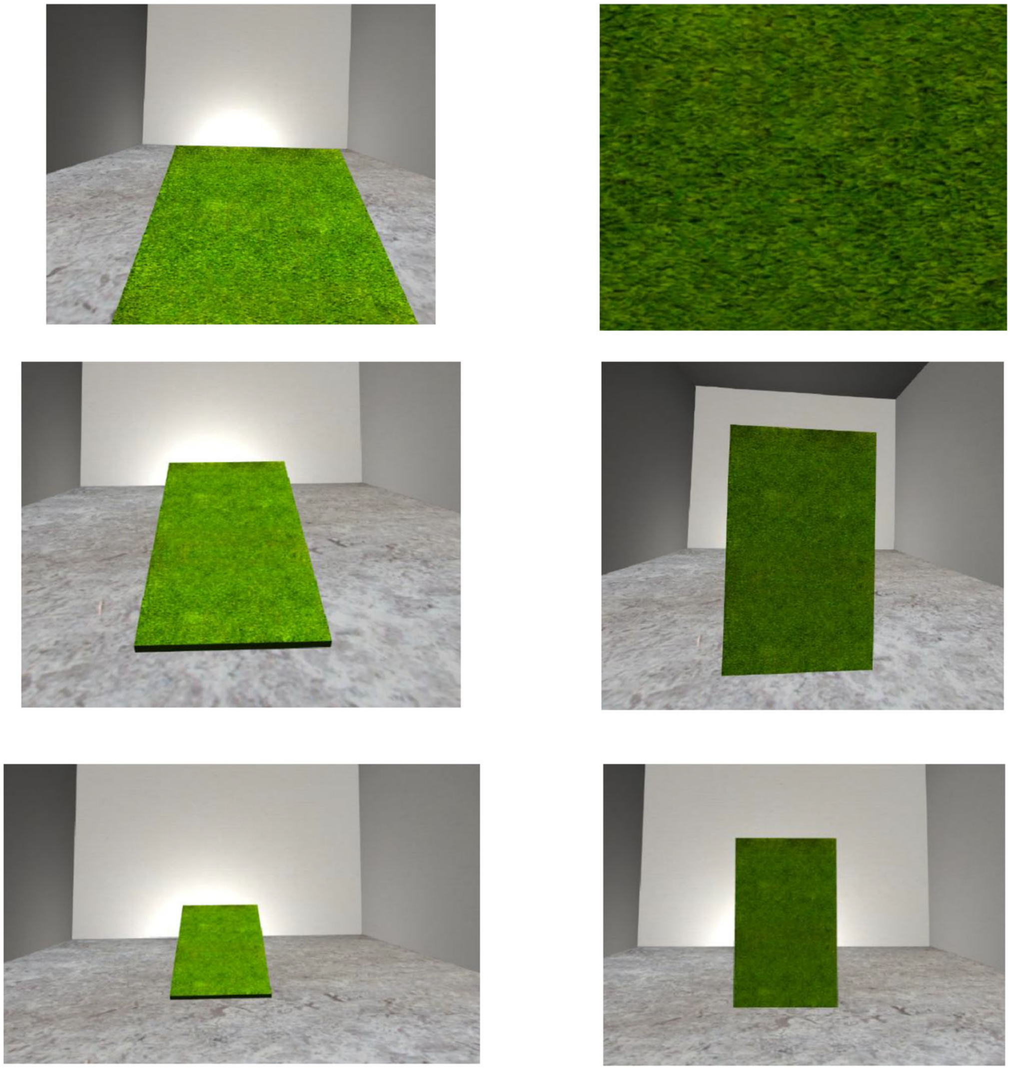

Figure 1. Sample trials for a 45 and 90 ramp at the near (top panel), mid (middle panel), and far distance (bottom panel) from the viewpoint of the observer in the VR.

controllers to record either a "yes" or "no" response and progressed through the trials at their own pace. In between trials the screen was completely black.

During the angle judgment task the ramps were presented in the same manner as in the affordance task, and the participant was asked to use their best judgment to estimate the angle of the presented ramp (0° to 90°). They reported their estimate out loud and it was recorded by the experimenter. The participant was also instructed to use a button on their controller to record their response time as soon as they said the angle out loud. For this condition, trials were advanced by the experimenter so that they had time to record the participant's responses. Angle responses were not recorded for one participant due to technical difficulties. Another participant discontinued participation after the affordance task, so no angle judgments were collected from him.

Table 1. Summary of results of the hypotheses (H1, H2) grouped by task, and applied to the various dependent measures.

Dependent variable	Extreme (high or low) value at task-relevant angle	Significant factor (H1) by task (H2)
Affordance perception task		
Affordance Judgment	n/a	**ETC**
$\text{Mean}_{\text{afford}}$	No (45°)	n/a
$\text{CV}_{\text{afford}}$	Yes (30°)	n/a
$\text{ETC}_{\text{afford}}$	Yes (30°)	n/a
Angle estimation task		
Angle Judgment	n/a	**Mean**, **CV**, ETC
$\text{Mean}_{\text{angle}}$	No (30° to 60°)	n/a
CV_{angle}	No (75°)	n/a
$\text{ETC}_{\text{angle}}$	No (15° to 60°)	n/a

Notes: Task-relevant angle for affordance is 30° (action boundary). Task-relevant angle for angle estimation is 45° (mid-point of range). Best moderators are in bold typeface, significant main effects are in light typeface. n/a means "not applicable".

Data reduction

In order to minimize the effects of response time outliers, but remove as little data as possible, we followed the recommendations for data reduction by Ratcliff (1993) and Grange (2015). For the affordance task, response times longer than 2 SD above the mean (M = 1.329s, SD = 1.205s) for the entire sample were removed. This eliminated any trials longer than 3.739 s, equivalent to 3.7% of all trials. For the angle estimation task, response times longer than 2 SD above the mean (M = 3.561s, SD = 3.283s) for the entire sample were removed. This eliminated any trials longer than 10.127 s, equivalent to 4.4% of all trials.

Results

The results were grouped by task (affordance and angle estimation) to reduce the complexity of statistical analyses. The summary of the results pertaining to the hypotheses is shown in Table 1. We tested whether a main effect of Angle was significant for all dependent measures, and whether the particular dependent measure was extreme (minimal or maximal) at a task-relevant angle. Hypothesis 1 was assessed by using affordance responses and latencies as dependent measures, and sway parameters (Mean, CV, ETC) as moderators in mixed-effects regression models. Hypothesis 2 was assessed qualitatively by comparing the pattern of results for the affordance task and the angle estimation task.

Affordance task

In order to test which sway parameter is significantly related to perception (consistent with Hypothesis 1), the data were analyzed with a mixed-effects hierarchical logistic regression on affordance judgments. The results of the analysis on affordance judgments are shown in Table 2.

Due to the constraints of mixed models the main effects and interactions of categorical variables were reported as paired comparisons (Mid vs. Far; Near vs. Far) using the far distance as the baseline condition. Overall, there was an effect of angle on affordance judgements, ($\beta = -0.19$, Standard Error $[SE] = 0.02$, $p < .001$). As the ramp angle

Table 2. Best fitting mixed-effects logistic regression model on affordance judgments. Significant effects are in bold font.

Factor	*β*	*SE*	*p*
Intercept	6.08412	0.78324	<0.001
Trial	0.00015	0.00638	0.98
Distance (Mid)	0.99617	0.87691	0.25
Distance (Near)	−0.58230	0.72607	0.42
Angle	**−0.19502**	**0.01787**	**<0.001**
Mean	2.23763	1.17773	0.06
CV	−0.04278	0.44635	0.92
ETC	0.36850	0.42609	0.38
Distance (Mid) × Angle	−0.01158	0.02495	0.64
Distance (Near) × Angle	0.02859	0.02095	0.17
Interactions of Mean with other terms			
Angle × Mean	−0.05421	0.03106	0.08
Distance (Mid) × Mean	1.22041	1.69385	0.47
Distance (Near) × Mean	0.81891	1.39439	0.55
Distance (Mid) × Angle × Mean	−0.04482	0.04832	0.35
Distance (Near) × Angle × Mean	−0.03524	0.03929	0.36
Interactions of CV with other terms			
Angle × CV	−0.00875	0.01532	0.56
Distance (Mid) × CV	−0.23960	0.75263	0.75
Distance (Near) × CV	−0.09205	0.58777	0.87
Distance (Mid) × Angle × CV	0.02723	0.02325	0.24
Distance (Near) × Angle × CV	0.01208	0.01933	0.53
Interactions of ETC with other terms			
Angle × ETC	−0.01127	0.01218	0.35
Distance (Mid) × ETC	**−1.28435**	**0.58718**	**0.03**
Distance (Near) × ETC	−0.12149	0.56948	0.83
Distance (Mid) × Angle × ETC	**0.04499**	**0.01716**	**0.01**
Distance (Near) × Angle × ETC	−0.00238	0.01586	0.88

increased the probability of Yes responses decreased and the probability of No responses increased. Consistent with past research on stand-on-ability perception (Hajnal et al., 2018; Malek & Wagman, 2008), the action boundary, i.e. the largest average angle at which at least 50% of the trials resulted in a 'yes' response, corresponded to 31.1 degrees (SD = 14.4°), which was not significantly different than 30°. There was a significant Distance (Mid vs. Far) × ETC interaction, ($\beta = -1.28$, $SE = 0.59$, $p = .03$). There was also a significant Distance (Mid vs. Far) × Angle × ETC three-way interaction, ($\beta = 0.04$, $SE = 0.02$, $p < .01$). The interactions indicated that out of all the movement parameters, ETC was related to affordance judgments (consistent with Hypothesis 1, see Table 1 for summary).

A 3 (Distance) × 7 (Angle) repeated-measures ANOVA was conducted on mean magnitude of head motion of affordance judgements ($\text{Mean}_{\text{afford}}$). The mean magnitude of head motion was based on the Euclidean distance time series of each trial. The main effect of Distance was significant, $F(1.178,32.985)=7.654$, $p = 0.007$, $\eta_P{}^2=0.215$, indicating that average head motion magnitude was largest in the Near condition. The interaction of Distance × Angle was significant, $F(4.703,131.689)=2.327$, $p = 0.05$, $\eta_P{}^2=0.077$. This captured the fact that head movement was at minimum at 45 degrees at the near distance, which does not correspond to the action boundary (see Figure 2).

The same analysis conducted on $\text{CV}_{\text{afford}}$ revealed that there was a main effect of Distance, $F(1.251,35.036)=16.824$, $p < 0.001$, $\eta_P{}^2=0.375$, indicating that CV was the largest at the near distance (see Figure 3). There was a main effect of Angle,

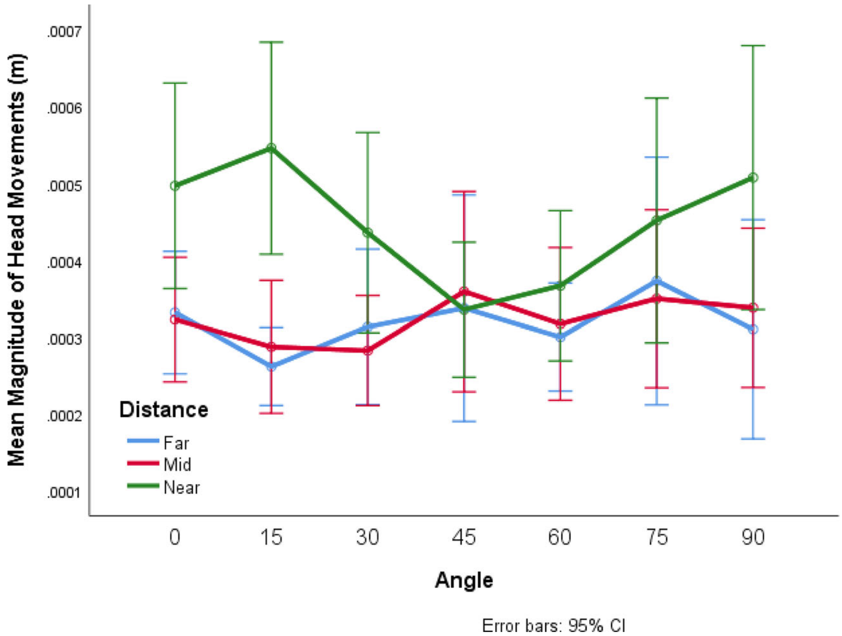

Figure 2. Mean magnitude of head movements (based on Euclidean distance time series) for affordance judgments as a function of distance and slope angle.

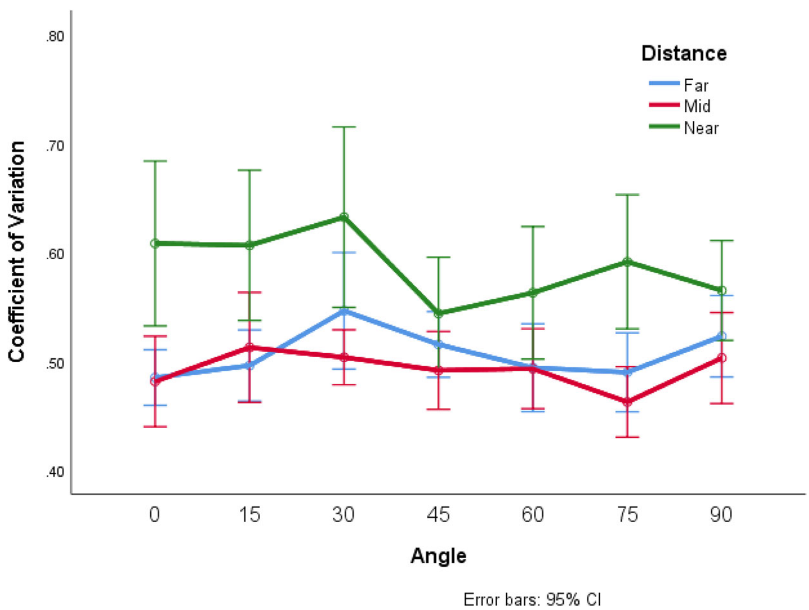

Figure 3. Coefficient of variation (standard deviation/mean) of head movements for affordance judgments as a function of distance and slope angle.

$F(4.362,122.126)=2.488$, $p=0.042$, $\eta_P{}^2=0.082$. The maximal CV was at 30 degrees, which corresponds to the affordance boundary (consistent with Hypothesis 1).

A 3 (Distance) × 7 (Angle) repeated-measures ANOVA was conducted on effort to compress (ETC_{afford}) of head motion for affordance judgements. There was a main

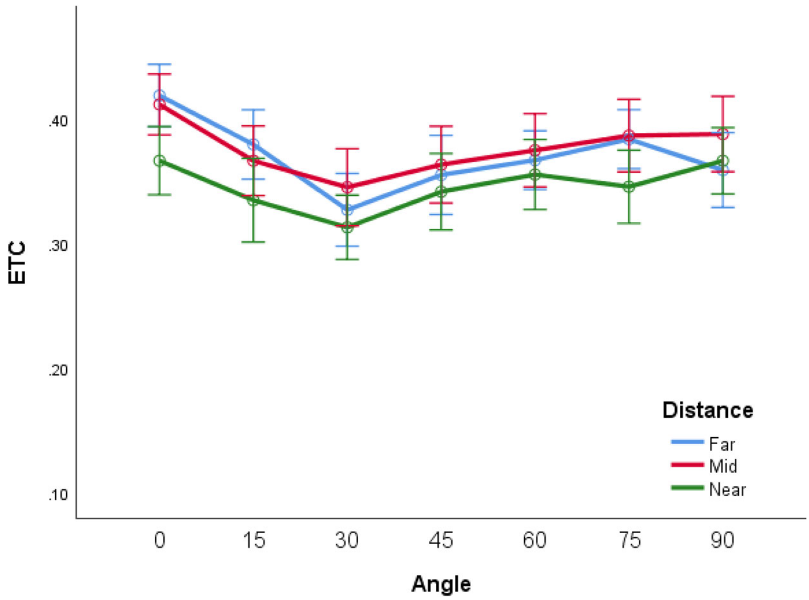

Figure 4. Effort-to-compress (ETC) of head movements for affordance judgments as a function of distance and slope angle.

effect of Distance, $F(1.567{,}43.866)=13.1$, $p < 0.001$, $\eta_P{}^2=0.319$, indicating that at Near distance, head movements are less complex (see Figure 4). There was a main effect of Angle, $F(6{,}168)=9.688$, $p < 0.001$, $\eta_P{}^2=0.257$. The minimum was at 30 degrees, corresponding to the affordance boundary. This correspondence indicates that ETC might be the best variable that uniquely characterizes affordance perception (consistent with Hypothesis 1 that predicted an extreme value of the dependent measure at the action boundary). The Distance × Angle interaction was not significant.

Angle estimation task

Table 3 reports the results of the regression analysis that was set up to explain which postural sway parameters moderated the influence of spatial variables on angle judgments.

The main effects of Distance (Mid vs. Far) ($\beta = -2.78$, $SE = 1.02$, $p < .01$), Distance (Near vs. Far) ($\beta = -2.33$, $SE = 1.01$, $p = .02$), Angle ($\beta = 0.97$, $SE = 0.01$, $p < .01$), and ETC ($\beta = -6.27$, $SE = 0.75$, $p < .01$) were statistically significant. Additionally, there were three significant two-way interactions, Distance (Mid vs. Far) × Angle ($\beta = 0.05$, $SE = 0.02$, $p = .02$), Distance (Near vs. Far) × Mean ($\beta = -2.8$, $SE = 1.19$, $p = .02$), and Distance (Near vs. Far) × CV ($\beta = -2.55$, $SE = 1.13$, $p = .02$). The significant negative main effect of ETC indicated that increase in complexity resulted in lower angle judgments. More importantly, the lack of significant interactions with ETC suggests that head movement complexity was not related to angle judgements compared to affordance judgements. This is consistent with Hypothesis 2 which stated that ETC should be a significant moderator of affordance judgments, but not angle judgments.

Table 3. Best fitting linear mixed-effects model of angle judgments. Significant effects are in bold font.

Factor	β	*SE*	*p*
Intercept	**12.17407**	**1.12593**	**<0.001**
Trial	0.02138	0.01203	0.076
Distance (Mid)	**−2.78260**	**1.02207**	**0.01**
Distance (Near)	**−2.33055**	**1.01099**	**0.02**
Angle	**0.97448**	**0.01341**	**<0.001**
Mean	0.88021	1.08790	0.42
CV	−0.68967	0.79622	0.39
ETC	**−6.26745**	**0.75232**	**<0.001**
Distance (Mid) × Angle	**0.04638**	**0.01952**	**0.02**
Distance (Near) × Angle	−0.00694	0.01920	0.72
Interactions of Mean with other terms			
Angle × Mean	0.00306	0.02017	0.88
Distance (Mid) × Mean	−2.23970	1.43005	0.12
Distance (Near) × Mean	**−2.80164**	**1.19481**	**0.02**
Distance (Mid) × Angle × Mean	0.02240	0.02687	0.40
Distance (Near) × Angle × Mean	0.00113	0.02189	0.96
Interactions of CV with other terms			
Angle × CV	0.00939	0.01557	0.55
Distance (Mid) × CV	0.83887	1.42724	0.56
Distance (Near) × CV	**−2.55390**	**1.13082**	**0.02**
Distance (Mid) × Angle × CV	−0.02630	0.02716	0.33
Distance (Near) × Angle × CV	0.03157	0.02126	0.14
Interactions of ETC with other terms			
Angle × ETC	0.02755	0.01417	0.052
Distance (Mid) × ETC	1.08934	1.10430	0.32
Distance (Near) × ETC	−0.79089	1.08608	0.47
Distance (Mid) × Angle × ETC	−0.00926	0.02030	0.65
Distance (Near) × Angle × ETC	0.01184	0.02027	0.56

There was a significant negative main effect of ETC ($\beta = -0.55$, $SE = 0.05$, $p < .01$). There was a significant Angle × Mean interaction ($\beta = -0.003$, $SE = 0.001$, $p = .02$). There was also a significant Distance (Near vs. Far) × ETC interaction ($\beta = -0.18$, $SE = 0.07$, $p < .01$). Additionally, there were two significant three-way interactions, Distance (Mid vs. Far) × Angle × Mean ($\beta = 0.004$, $SE = 0.002$, $p = .02$), and Distance (Near vs. Far) × Angle × Mean ($\beta = 0.003$, $SE = 0.001$, $p = .05$).

Similarly to the affordance task, we conducted a series of ANOVAs to assess how movement parameters depend on spatial configuration of the stimuli. A 3 (Distance) × 7 (Angle) repeated-measures ANOVA was conducted on mean magnitude of head motion for angle judgements ($\text{Mean}_{\text{angle}}$). There was a main effect of Distance, $F(1.06,29.62)=21.22$, $p < 0.001$, $\eta_P{}^2=0.43$. The main effect of Angle was also significant, $F(3.06,85.57)=4.04$, $p = 0.009$, $\eta_P{}^2=0.13$, indicating that head motion magnitude varies as a function of presented angle. There was also a significant interaction of Distance × Angle, $F(3.67,102.68)=10.78$, $p < 0.000$, $\eta_P{}^2=0.28$. Post hoc results (based on Bonferroni comparisons) indicate that $\text{Mean}_{\text{angle}}$ for all three distances is different than each other, and that head movements are larger at Near distances and they flatten and bottom out in the 30 to 60 degree range, widely overlapping with the action boundary and the arithmetic midpoint of the range. This weak correspondence with "anchor" ramp angles (either the affordance boundary at 30° or arithmetic midpoint of range at 45°) indicates that $\text{Mean}_{\text{angle}}$ may not be the best variable to explain numeric judgments in an angle estimation task. Figure 5 shows the change in mean head motion across angles and distances.

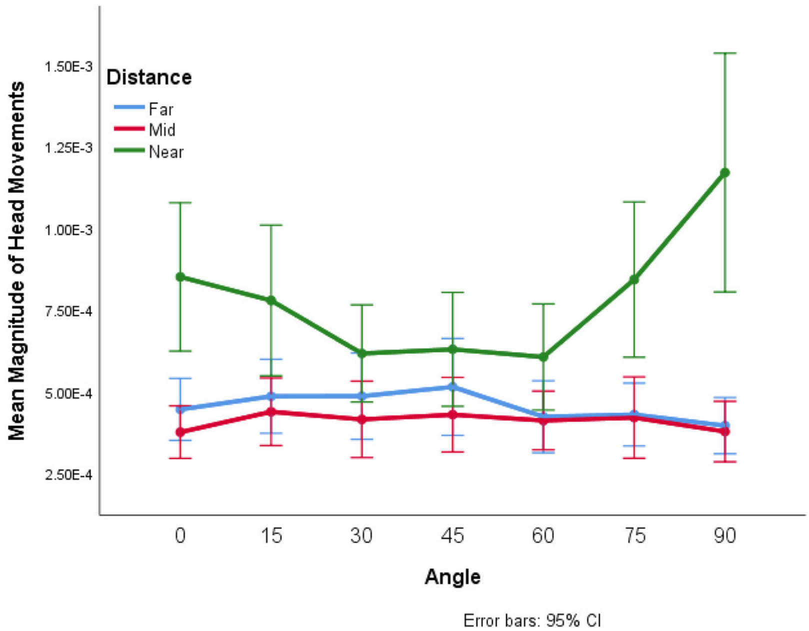

Figure 5. Mean magnitude of head movements for angle judgments as a function of distance and slope angle.

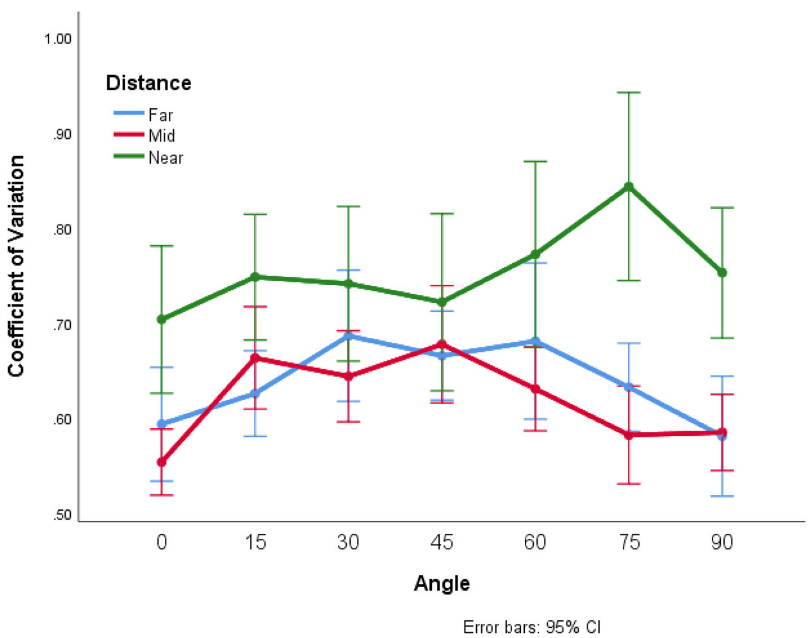

Figure 6. Coefficient of variation of head movements for angle judgments as a function of distance and slope angle.

A 3 (Distance) × 7 (Angle) repeated-measures ANOVA was conducted on coefficient of variation of head motion for angle judgements (CV_{angle}). There was a main effect of Distance, $F(1.26,35.26)=16.47$, $p < 0.001$, $\eta_P^{\,2}=0.37$. Post hoc Bonferroni comparisons

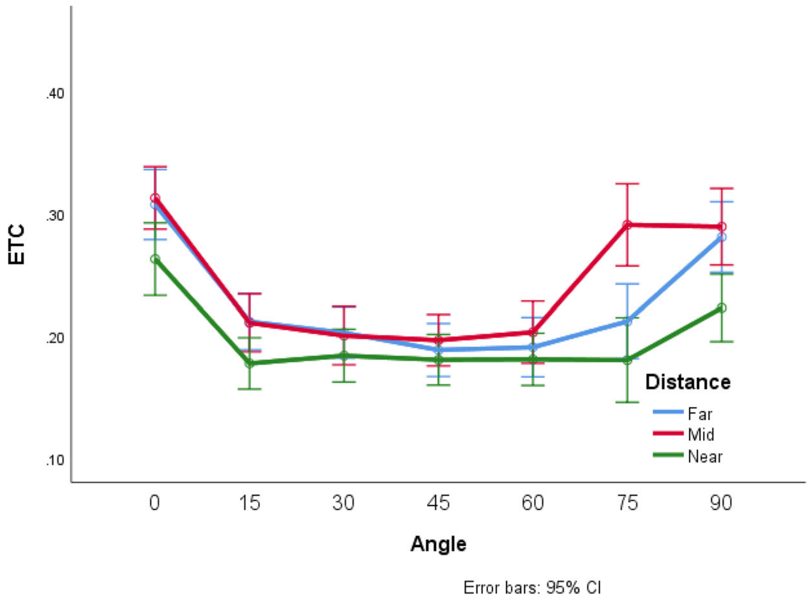

Figure 7. Effort-to-compress (ETC) of head movements for angle judgments as a function of distance and slope angle.

indicated that Near distances have larger CV values than Mid and Far distances. The maximal CV for the near distance ramp was at 75°, not corresponding with the affordance boundary, nor the midpoint of the range of angles (see Figure 6). There was a main effect of Angle, $F(3.79,106.23)=4.89$, $p=0.001$, $\eta_P{}^2=0.15$. There was a significant interaction of Distance x Angle, $F(6.74, 188.73)=3.01$, $p=0.006$, $\eta_P{}^2=0.10$.

A 3 (Distance) × 7 (Angle) repeated-measures ANOVA was conducted on ETC of head motion during angle judgements. There was a main effect of Distance, $F(1.61,45.11)=35.56$, $p<0.001$, $\eta_P{}^2=0.56$. Post hoc Bonferroni comparisons indicated that all distances are different than each other with the near distance ramp trials showing the lowest ETC values. There was a main effect of Angle, $F(3.77,105.51)=58.12$, $p<0.001$, $\eta_P{}^2=0.68$. There was a significant interaction of Distance × Angle, $F(12,336)=8.634$, $p<0.001$, $\eta_P{}^2=0.24$. As the pattern of results indicates in Figure 7, there was a wide range of angles (15° to 60°) at which ETC_{angle} was at minimum for all distances. This demonstrated weak sensitivity to either the action boundary or the arithmetic midpoint of the range.

Discussion

The two main goals of the present study were to 1) demonstrate that complexity of exploratory activity, not magnitude and variability, is related to perceptual performance (Hypothesis 1), and 2) test whether complexity is related to performance in functional tasks such as affordance perception, or nonfunctional tasks such as numeric estimation of slant angle (Hypothesis 2). Both goals tap into critical aspects of perception: the former tests the importance of complex exploratory activity for perception, whereas the latter tests whether functional tasks are better suited at demonstrating the nature of the connection between perception and action than nonfunctional tasks. In the affordance task complex exploratory activity was sensitive to the action boundary such that ETC was the lowest at 30°. No unique pattern of ETC values was observed as a function of slant in the numeric angle estimation task. This is not surprising, since affordance perception is directly linked to action possibilities, thus complex postural sway parameters during the affordance task were more sensitive to action boundaries.

Affordance perception and numerical estimation are different functions of spatial layout and postural sway

Our present analyses revealed that affordance judgments are a function of slant and distance, moderated by the effects of ETC. Complexity of head sway was a significant moderator, but Mean and CV were not, suggesting that perceptual performance is related to the complexity of exploratory activity, not to magnitude or variability (Hypothesis 1). Our results about the value of the complex nature of exploratory activity are consistent with other researchers who have demonstrated that only a particular type of complex pattern of postural sway, inserted as a vibratory pattern of pink noise into shoe soles of elderly patients, facilitates maintenance of balance and prevents falls (Priplata et al., 2002). This reinforces the need for looking into the deep structure of exploratory activity as having a complex, nonrandom nature, independent of gross measures of central tendency and variability. Numeric estimation judgments were also influenced by both distance and slant, moderated by Mean, CV, and ETC. The fact that Mean and CV were also significant moderators (see results in the last column of Table 1 for angle responses) leads us to speculate that in numeric estimation tasks participants may have employed cognitive strategies. This is consistent with the relatively underspecified nature of the numeric estimation task that was not paired with any behavioral function or goal. Participants may have consciously chosen to move more or less with more or less variability based on some yet to be determined cognitive strategy in order to inform their judgments. While it is plausible to assume that the magnitude and variability of postural sway can be consciously controlled, it is hard to conceive of a conscious cognitive process that can direct the body to move in more or less complex ways. Just like the patients in Priplata et al.'s study were not consciously aware of the nature of subthreshold vibration patterns in their shoe insoles, it is plausible to assume that participants in the current study were also not consciously aware of the kinds of complex movement patterns they were producing. Whether complexity of postural sway is subject to volitional control is a speculative conjecture that should be the subject of future research in order to differentiate direct perception from cognitive tasks (Heft, 1993; Norman, 1980).

Action parameters engender task-specific effects of exploratory activity

In a series of ANOVA analyses we used the action parameters (Mean, CV and ETC) as dependent measures to reveal how exploratory activity generated by head sway was affected by spatial layout in both tasks. Again, the results revealed different pattern of dependency on spatial layout, unique to each task. Mean magnitude of head movements during the affordance task was minimal at 45° for near distances. This indicated that the mean magnitude was not specific to the action boundary at 30° (see Figure 2), thus reinforcing the mixed modeling results where we revealed that $\text{Mean}_{\text{afford}}$ was not a significant moderator of affordance judgments. At the same time, $\text{Mean}_{\text{afford}}$ was significantly larger at near distances compared to mid and far distances, possibly due to the ramp surface being too close to the observer, and thus needing more exploration to reach an affordance judgment. $\text{Mean}_{\text{angle}}$ was also minimal in the broad range from 30° to 60° at near distances for numeric estimation of slant (see Figure 5). The wider range of minima showed less task-specificity, consistent with the underspecified nature of the task itself.

The coefficient of variation (CV) was largest at near distances in both tasks, indicating that more varied exploratory patterns were needed to reach a judgment at near distances, again perhaps due to the extreme proximity of the ramp to the observer. Task specificity was exhibited at near distance in the affordance task, as peak $\text{CV}_{\text{afford}}$ was measured at the action boundary (see Figure 3). No such task specificity was documented in the numeric task, as CV_{angle} was maximal at 75° in the near distance condition (see Figure 6).

ETC, the measure of complexity of exploration, was minimal at near distances as compared to mid and far distances. This suggested that postural sway was least complex for stimuli near the observer, consistent with past research on the effects of distance on postural sway (Bonnet et al., 2010; Hajnal et al., 2014). Consistent with Hypothesis 2, $\text{ETC}_{\text{afford}}$ was minimal at 30° in the affordance task, suggesting high sensitivity to the action boundary (see Figure 4). This result is also in line with past empirical findings where it was shown that an extreme value of certain dependent measures (e.g. confidence judgments) was a good indicator of the action boundary (Fitzpatrick et al., 1994). In the numeric estimation task such sensitivity was mostly absent as $\text{ETC}_{\text{angle}}$ bottomed out over a much larger range between 15° and 75° (see Figure 7). This pattern of results indicated that $\text{ETC}_{\text{afford}}$ was a significant indicator of task-relevant properties (i.e. action boundary) in affordance judgments, consistent with the mixed effects modeling that proved $\text{ETC}_{\text{afford}}$ to be the most valuable moderator of the effects of spatial layout on affordance judgments. These results were consistent with our generic predictions and Hypothesis 2 about the value of ETC as a significant factor related to responses in an affordance task.

Complexity as a moderator of spatial effects in affordance perception

Our study adds to a growing body of literature that shows how exploratory activity relates to perception (Mark et al., 1990; Stoffregen et al., 2005). Complexity of exploration, measured by ETC, was significantly related to responses, but only in the affordance task. This result is consistent with recent empirical findings in a variety of affordance tasks in which complexity of body movements was associated with perception of reachability (Doyon et al., 2021; Masoner et al., 2020), aiming (Jacobson et al., 2021), spatial extent (Palatinus et al., 2014), and standonableness (Doyon et al., 2019, Hajnal et al., 2018). Complexity is (1) a par excellence conduit of the effects of spatial layout on affordance perception, and (2) integral part of how a specifying variable of affordance perception might be generated through changes in optical and gravitoinertial patterns of stimulation. We speculate that exploratory activity (constrained by spatial layout and task) generates information. This pattern is best described by measuring the complexity of body movements. Complexity parameters (e.g. ETC, multifractal spectrum width) capture unique occasions of affordance perception, such as when the perceiver detects an action boundary. To the extent that perception is in direct service of guiding behavior, psychophysical studies of perception should move away from soliciting non-functional numeric judgments as they do not relate closely to relevant actions (affordances). Unfortunately, the extant literature does not readily make this distinction, and oftentimes conflates numerical estimation tasks with affordance tasks (Proffitt, 2006).

Our present investigation is preliminary to any investigation about the nature of the information that specifies the organism-environment relationship in goal directed tasks. The current results provide the basis for the conjecture that the specifying information pattern is most likely a consequence of the complexity of postural sway, and not due to its mere magnitude or variability. This is consistent with the fact that complexity, rather than magnitude or speed of postural sway is a significant factor for maintaining postural stability (Zhou et al., 2017).

The discovery of the exact role of exploratory activity in affordance perception holds the promise of advancing the field of perception and action research. Future studies are required to demonstrate whether complex exploratory activity is causally linked to affordance perception. In particular, perception of affordances in conditions where exploratory activity is freely available should be compared with perception in conditions in which exploratory activity is restricted or outright prevented.

Acknowledgments

The research reported in this paper and in part carried out at the Budapest University of Technology and Economics (BME) has been supported by the NRDI Fund (TKP2020 NC, Grant No. BME-NC) based on the charter of bolster issued by the NRDI Office under the auspices of the Ministry for Innovation and Technology, Hungary.

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