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RESEARCH ARTICLE

Mind the step: complementary effects of an implicit task on eye and head movements in real-life gaze allocation

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Abstract Gaze in real-world scenarios is controlled by a huge variety of parameters, such as stimulus features, instructions or context, all of which have been studied systematically in laboratory studies. It is, however, unclear how these results transfer to real-world situations, when participants are largely unconstrained in their behavior. Here we measure eye and head orientation and gaze in two conditions, in which we ask participants to negotiate paths in a real-world outdoor environment. The implicit task set is varied by using paths of different irregularity: In one condition, the path consists of irregularly placed steps, and in the other condition, a cobbled road is used. With both paths located adjacently, the visual environment (i.e., context and features) for both conditions is virtually identical, as is the instruction. We show that terrain regularity causes differences in head orientation and gaze behavior, specifically in the vertical direction. Participants direct head and eyes lower when terrain irregularity increases. While head orientation is not affected otherwise, vertical spread of eye-in-head orientation also increases significantly for more irregular terrain. This is accompanied by altered patterns of eye movements, which compensate for the lower average gaze to still inspect the visual environment. Our results quantify the importance of implicit task demands for gaze allocation in the real world, and imply qualitatively distinct contributions of eyes and head in gaze allocation. This underlines the care that needs to be taken when inferring real-world behavior from constrained laboratory data.

Keywords Gaze · Eye movements · Head orientation · Natural environment · Terrain negotiation · Visuomotor routines

Introduction

During natural behavior, humans shift their gaze to sample the visual environment in detail to gather information needed for skilled behavior. Research on natural gaze shifts has largely focused on eye movements (Buswell 1935; Yarbus 1967), although humans typically shift gaze by coordinated movements of head and eyes. Indeed, even laboratory experiments that match stimuli to real-world input have only limited predictive power about real-world gaze allocation (’t Hart et al. 2009; Foulsham et al. 2011). To what extent do real-world behavioral constraints implicitly influence eye-in-head and head-in-world movements when selecting relevant information?

Bottom-up models of gaze allocation assign a probability to attract attention (“saliency”) to each stimulus region based on its visual features (Itti and Koch 2000), possibly including spatiotemporal context, prior knowledge on stimulus statistics (Torralba 2003; Võ and Henderson 2011) and spatial biases (Tatler 2007). Top-down approaches, in contrast, relate the preferably attended regions to an explicitly defined task, frequently using visual search (Treisman and Gelade 1980; Wolfe et al. 1989; Wolfe 2007). Although search allows quantitative modeling of task-driven gaze allocation and is an enterprise humans engage in reasonably frequently, it is hardly the most common or “natural” mode of human behavior. Here we therefore consider natural task sets, which are not given explicitly by instruction, but implicitly by constraints of the real world.

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In real life, an organism is partially free to choose its current "task" and update this choice continuously. Intentions affect not only the processing of specific object features (Hannus et al. 2005) and change detection (Triesch et al. 2003), but also gaze directly (Castelhano et al. 2009; Rothkopf and Ballard 2009). As predicting the trajectory of a bouncing ball by making eye movements to upcoming relevant locations exemplifies (Hayhoe et al. 2005), gaze adapts to increasing knowledge of the environment's physical properties. Recently, wearable eye trackers have made studying gaze in real-life scenarios feasible. However, most research in this area has restricted itself largely to either free exploration (Cristino and Baddeley 2009; 't Hart et al. 2009; Schumann et al. 2008) or specific—thus experimentally readily controllable—domains (Hayhoe and Ballard 2005; Kandil et al. 2009; Land et al. 1999; Land and McLeod 2000). In free exploration, there is no explicit instruction and the participant implicitly selects their task. In the other scenarios, the task (e.g., sandwich making, driving, tea making, cricket) typically specifies the full range of actions to be taken and does not leave much room for directing gaze at other locations. In contrast, walking outdoors is a natural task that leaves considerable room for visual exploration (Calow and Lappe 2008; 't Hart et al. 2009), while part of the task is constrained by the path to be followed. Here we use walking as scenario in which visual environment, context and instruction are held constant, while we control the implicit part of the task (e.g., not tripping) by varying terrain regularity.

When the head is unconstrained, the orientation of the eye is offset against changes of the orientation of the head via the vestibuloocular reflex (VOR). Similarly, the vestibulocollic reflex (VCR) stabilizes head-in-world orientation during larger body movements while VOR is suspended (Guitton and Volle 1987). The way these movements interact to direct gaze has been investigated in real-life tasks, such as making tea (Land et al. 1999) and driving (Land 1992). In both tasks, large gaze changes are accompanied by head movements proportional to the gaze change, but head movements are smaller when body movements are made as well (Land 2004). Similar patterns of interaction between these three types of movements have been found in a walking task in a laboratory setting on even terrain (Imai et al. 2001). With respect to terrain regularity, the relative importance of the lower visual field for negotiating irregular terrain has been shown by blocking downward viewing (Marigold and Patla 2008) and by tracking gaze while participants walked a short, irregular path in the laboratory (Marigold and Patla 2007; Patla and Vickers 2003). By varying terrain regularity and tracking eye-in-head and head-in-world movements, we combine these two approaches to assess real-world gaze allocation.

Walking is a complex task (Hausdorff et al. 2005), which uses a variety of visual (Hayhoe et al. 2009; Bardy et al. 1996; Calow and Lappe 2008; Warren et al. 2001) and vestibular (Fitzpatrick et al. 1999; Jahn et al. 2000) cues. When walking on an obstacle course or in traffic, collision avoidance is crucial. In these cases, items to be dealt with—obstacles (Ballard and Hayhoe 2009), locations where cars likely appear (Geruschat et al. 2003) or pedestrians with high collision probability (Jovancevic-Misic and Hayhoe 2009)—attract gaze. It is conceivable that such gaze attraction extends to terrain irregularities that must be negotiated. During walking, there indeed is an abundance of downward-directed eye movements ('t Hart et al. 2009; Calow and Lappe 2008), which emphasizes the importance of the lower visual field (Marigold and Patla 2008; Timmis et al. 2009). Visual information is indeed used to increase foot placement precision (Chapman and Hollands 2006a; Hollands and Marple-Horvat 1996), demonstrating a link between the sampling of visual information on the terrain and phases of the step cycle, and suggesting specific visuomotor routines for organizing walking (Imai et al. 2001). The role of these routines becomes evident when they are disturbed, such as in the elderly (Cavanagh and Higginson 2002; Chapman and Hollands 2006a; Jahn et al. 2010; Startzell et al. 2000) or patients suffering from Parkinsonian syndromes (Pinkhardt et al. 2008). In analogy to restrictions imposed by bodily or sensory impairments, variation in terrain regularity may affect the sampling of visual information in healthy participants.

In laboratory studies, terrain regularity correlates with look-ahead distance on the path (Marigold and Patla 2007; Patla and Vickers 2003). The artificially sparse environment, however, makes looking at the surroundings serve little purpose, and thus may evoke gaze behavior different from real-world situations. One study that investigated gaze on path in a real-world setting (Pelz and Rothkopf 2007) found that on more difficult terrain, the fraction of time the path is fixated increased, while many other gaze parameters remained unaltered. However, this study manipulated path difficulty together with changing the environment, such that it cannot be fully excluded that this change in surroundings accounts for some of its results. To the best of our knowledge, no study to date has addressed the relation between real-life gaze allocation and terrain difficulty without substantial changes to the visual environment. Eventually, such measurements will be necessary to verify the ecological validity of laboratory measurements on walking for real-world situations. Here we use a wearable eye tracker to measure gaze during walking in a real-world setting with varying terrain difficulty and nearly identical visual environment. Although the present study is about gaze allocation rather than about walking *per se*, it may provide one step to take walking to the real-world. Therefore, if combined with more sophisticated gait measurements, real-life gaze measurements as reported here may eventually also present an important complement to laboratory studies on walking.

More specifically, in the present study, participants walk up and down an inclined street, while their eye-in-head movements and head-in-world orientation are tracked with a novel, wearable eye-tracking device ("EyeSeeCam"; Schneider et al. 2009). In the two experimental conditions, instructions and visual environment are virtually identical, but terrain regularity is varied by using a set of irregularly placed steps in one condition and the comparably smooth road running in parallel to the steps in the other condition. This procedure allows us for the first time to quantitatively assess in a realistic scenario how different contributions to gaze direction depend on an implicit task set (safely negotiating terrain) with all other parameters (environment, instruction, etc.) held constant.

Materials and methods

Participants

Eight volunteers (4 male, 4 female; mean age ± SD: 30.3 ± 7.1 years) with normal or corrected-to-normal vision and no walking deficits participated in this experiment. All participants gave written informed consent before the experiment. The experiment conformed to institutional and national regulations and the Declaration of Helsinki.

Conditions

The main experiment took place in a local street ("Hirschberg") that has a sidewalk with irregularly placed steps on one side (Fig. 1a). The main street is an inclined cobbled road. The sidewalk and main street are separated by a metal railing. Participants walked on the road as well as on the steps, close to this railing. Since this was repeated for walking up and down, each participant walked through the street a total of four times. To counter any effects of order on behavior, the order of the four walks was randomized. To allow randomization of recorded walks, two participants had to make one extra unrecorded walk and another participant two to get to the starting point. Since pilot data from a different experiment indicated that repetition of walks on the time scale considered here has no measurable influence on gaze behavior, we are confident that these extra walks do not have any effects on the results. The path that was to be taken was explained to the participants right before the walk, and the instruction for each of the four walks was to "walk as you normally would.". That is, with the exception of whether to use steps or road, instructions were exactly identical in all conditions. As the environment remains unchanged as well, the only difference between conditions, which we will refer to as "road" (Fig. 1d, f) and "steps" (Fig. 1e, g), is the implicit task set of negotiating terrain of distinct difficulty.

To verify that other environments induce qualitatively similar eye movements, six of the eight volunteers participated in two additional conditions, referred to as "stairs" and "alley". In the "stairs" condition, they walked up and down a continuous flight of stairs, which is considerably more regular than the "steps" condition. In the "alley" condition, they walked a path with negligible incline compared with the "road" condition (Fig. 1h, i). Both of these terrains were located at one end of the street where the main experiment took place: the old, uneven "stairs" leading to the market square and the "alley" to another street. These extra conditions were always recorded following the main conditions in the order "stairs" and "alley".

Since the alley and stairs were considerably shorter than the inclined road and steps, recording time in the main conditions "steps" and "road" were longer than in the conditions "alley" and "stairs". On average, participants took 59.81 s ± 3.00 s (mean ± SD) for "steps", 51.87 s ± 7.76 s for "road", 11.56 s ± 1.91 s for "alley" and 12.67 s ± 2.14 s for "stairs".

Setup

In all conditions, eye movements were recorded during the walk with a mobile, wearable eye tracker ("EyeSeeCam"; Schneider et al. 2009; Fig. 1b). The eye tracker recorded the eye-in-head signal at 305 Hz for both eyes. If only the signal from one eye was available, the signal of this eye was used; otherwise, the average gaze of both eyes was used for all distribution analyses. Since the look-ahead distance was typically large compared with the eye distance, deviations between the gaze of both eyes due to vergence movements were negligible. The signal was missing for 13.3 % of time in the left eye, 13.9 % in the right eye and 8.8 % for the joint signal of both eyes. We did not observe any dependence of missing data on terrain (road/steps), walking direction (up/down) or an interaction between these factors (all $p > .212$, ANOVA). In addition, a camera fixed to the forehead recorded a movie of the environment with a wide-angled lens ("head-cam") and a camera moving with the direction of gaze recorded a gaze-centered movie. In the present study, we used this gaze-centered video to verify the eye-in-head calibration online (by having participants look at designated objects and points, before and between measurements) and the head-

Fig. 1 Setup and conditions. **a** Local street, in which experiments were conducted. "steps" are to the right, "road" to the left of the handrail. **b** EyeSeeCam device. **c** A vanishing point's location in the head-centered video can be used to estimate head-in-world orientation. If the head moves *down*, the vanishing point moves up in the movie and vice versa. **d**–**g** First frame of analyzed data of the same participant for the main conditions. *Circles* indicate vanishing point (see Methods): **d** up/road, **e** up/steps, **f** down/road, **g** down/steps. **h** The "alley" control condition. **i** The "stairs" control condition

centered video to determine head-in-world orientation off-line.

The EyeSeeCam software defined the origin for eye-in-head orientation as a straight-ahead direction relative to the device, such that there was some variability (up to a few degrees) between individuals. Similarly, the head-in-world orientation (see below) was defined relative to device-centered reference frame (the head-cam). Since the camera was not removed from the participant throughout the experiment and there was only little slippage of the goggles to which the device was mounted, the definition of the origin was consistent across all conditions. Hence, none of the differential effects between conditions could be confounded by the choice of reference frame. In addition, for the determination of gaze (eye-in-world), the offsets of the two device-centered origins compensated each other, such that the gaze coordinate systems of different individuals were identical.

Eye-in-head orientation

To analyze eye-in-head orientation, the eye-tracker data were separated in a horizontal and a vertical component. For each component, we determined the mean and the standard deviation of the eye-in-head orientation. We quantified the dependence of these parameters on terrain (road/steps) and walking direction (up/down) by a two-factor ANOVA.

Head-in-world orientation

As a proxy for head-in-world orientation, we determined the position of a point at ground level beyond the end of the walking track in frame coordinates in the head-centered movies. In loose analogy to descriptive geometry, we refer to this point as the vanishing point. The definition of this point depended on environment and necessarily on walking direction (up/down). Since environment was identical for "steps" and "road" and the line of sight was much longer than the width of the used path (steps and road combined), the vanishing point was virtually independent of terrain. Consequently, none of the differences between the two terrains were attributable to the vanishing point definition. In contrast, the vanishing point definition might in principle confound the effects of walking direction. However, since we are interested in the factor terrain, the effect of walking direction remains irrelevant, unless we would observe an interaction between walking direction and terrain.

To determine the vanishing point, we used the following semi-manual procedure. First, a pixel was selected by clicking on the frame with a mouse pointer in every 30th frame (i.e., every second) as the vanishing point for this frame. To determine the vanishing point in the remaining frames, the region around the vanishing point was identified in the 29 frames temporally adjacent to each annotated frame (14 before, 15 after) by a correlation-based template-matching procedure. A square region around the vanishing point in the annotated frame was used as template. The regions with the highest 2D correlation to this original region were then chosen as matching regions in the frames before and after each annotated frame. The center of this matching region was then defined as the vanishing point in those frames. The correctness of this procedure was verified through visual inspection. This procedure returned for every frame the vanishing point in pixel coordinates. To transform this result into head-in-world orientation (i.e., into degrees of visual angle), the "fish-eye" distortions of the head camera needed to be corrected for. We did so by using the Camera Calibration Toolbox for Matlab (Bouguet 2010). Knowing the opening angle of the camera (120° × 70°), the normalized coordinates resulting from this computation could be converted into an angular signal for head-in-world orientation using the same unit as the eye-in-head signal (degrees of visual angle), which makes the two signals commensurate. By analyzing the distribution of the vanishing point's position in the head-centered movies, we could therefore assess the contribution of head-in-world orientation to terrain-induced changes of gaze direction (Fig. 1c).

Gaze-in-world

For each head-in-world sample, eye-in-head orientation and head-in-world orientation signals were added to obtain a gaze-in-world signal (cf. Land and Tatler 2001). Both the vertical and horizontal component of this signal were tested for their dependence on walking direction (up/down) and terrain (road/steps) using a two-factor ANOVA.

The factor walking direction was in part influenced by the experimental setting (e.g., choice of vanishing point, slight shifts in vantage point); hence, it needed to be ensured that the factor did not interact with terrain. This was the rationale to include it in the statistical analysis, although main effects of walking direction itself need to be interpreted with care.

Fast and slow eye movements

The raw orientation signals of head and eye allowed an estimate of where gaze was directed in the environment. To quantify how different types of eye movements contributed to this, we considered the direction and amplitude distributions separately for saccades and slow movements. Unlike in head-fixed conditions, classifying eye movements from head-free data under free-movement conditions presents a considerable challenge. We therefore opted to merely distinguish "fast" from "slow" eye movements. Though it is likely that the bulk of fast movements resulted from actual saccades, we will refrain from using this term, as other fast movements might be included, too. Slow movements were likely an agglomerate of different eye-movement types (including fixations), which could not be dissociated further with the data available.

Although vergence was typically negligible, missing datapoints in one eye (and thus changing from average to one-eye signal) could yield sudden jumps in the signal. Hence, the eye-movement classification was performed separately for each eye and combined within each subject prior to statistical analyses. First, we applied a velocity threshold of 40°/s to detect "fast" movements. Fast movements of durations longer than 200 ms were discarded from analysis, as they were unlikely saccades. Second, the intervals in between fast movements were designated "slow" eye movements. Movements starting or ending with a missing sample were discarded, as were eye movements containing two consecutive missing samples or consisting of more than 10 % missing samples. This procedure resulted in a set of slow eye movements and a set of fast eye movements.

Each eye movement in each set was then characterized by four values: the Cartesian coordinates (x/y) of their starting location, their direction and their amplitude. Starting points were binned in 5° × 5° degree bins. In each of these spatial bins, we computed the average direction (ignoring amplitudes by first normalizing each vector to unit length and then computing the mean direction). This resulted in a total of 4 maps per participant: 2 terrains and 2 speeds (fast/slow).

The distributions of eye-movement starting points were very different between the terrains, which prohibited a direct bin-wise comparison of the distributions across terrains. Consequently, comparisons of direction were made between fast and slow movements within each terrain only. For direction of the eye movements, we used a Watson–Williams test, which compares the means of two sets of circular data. To make comparisons between the two types of terrain, we subsequently pooled over all bins (i.e., ignored the starting point of the movement). The distribution of directions was compared between road and steps for both the fast and slow eye movements using a Watson's test for the homogeneity of two samples of circular data. Median eye-movement amplitudes in each participant were compared for direction intervals centered at those two directions that dominated over the others (upward and downward, see Results) using Welch's *t* tests (a *t* test version that accounts for unequal variance) for slow and fast movements separately.

Results

Gaze-in-world

To investigate the effect of implicit task sets on gaze allocation, participants negotiate different real-world terrains, during recording of their eye-in-head and head-in-world orientation. Before addressing the separate contributions of head-in-world movements and eye-in-head movements to gaze, we analyze the combined signal; that is, the distribution of gaze (data of statistical analyses in Table 1). Since saccades are of short duration and these distributions are sampled uniformly in time, distributions are dominated by slow movements, which include fixations. This analysis thus is comparable to considering fixation distributions, as is frequently done in laboratory studies; a split in fast and slow eye movements is deferred to section "Fast and slow eye movements". Visually inspecting the raw distributions of gaze, one observes two distinct peaks on both types of terrain (road/steps). In the road condition (Fig. 2a), one peak is centered near the vanishing point and one peak falls about 20° below that, presumably on the path itself. In the steps condition (Fig. 2b), this second peak is more pronounced and located about 10° lower than in the road condition, while the central peak remains virtually at the same location. Horizontally, all peaks are close to the midline. The difference between both conditions is a first qualitative indication that effects of terrain act mostly along the vertical axis.

In the horizontal, mean gaze direction depends significantly on walking direction (Fig. 3a), but not on terrain, and there is no interaction between the two factors. In contrast, the mean vertical gaze direction is affected by terrain only, whereas the effect of walking direction and the interaction are not significant.

In addition to the mean direction of gaze, the aggregate data (Fig. 2) suggest a wider spread of gaze in the vertical for the steps condition. To quantify this, we compute the standard deviation of the horizontal and vertical gaze component (Fig. 3b). In the horizontal, there is no significant main effect of terrain or walking and no interaction. In contrast, the vertical component shows an effect of terrain but no effect of walking direction or an interaction between the two factors.

Table 1 ANOVA results

			horizontal			vertical		
			terrain	direction	terrain * direction	terrain	direction	terrain * direction
GAZE	mean	F	0.70	**9.41**	1.28	**21.84**	0.07	2.18
		p	.408	**.005**	.268	**< .001**	.795	.151
	spread	F	1.88	0.04	0.54	**19.27**	0.002	0.39
		p	.181	.843	.469	**< .001**	.968	.535
EYE	mean	F	0.72	0.25	0.37	**16.75**	6.62	0.72
		p	.403	.622	.548	**< .001**	.016	.403
	spread	F	0.19	0.06	5x10^{-4}	**14.67**	0.02	1.11
		p	.664	.806	.982	**< .001**	.902	.301
HEAD	mean	F	0.12	**26.01**	1.92	**12.78**	**9.78**	1.01
		p	.734	**< .001**	.177	**.001**	**.004**	.323
	spread	F	1.25	1.10	0.17	2.43	0.10	0.006
		p	.273	.304	.681	.130	.755	.938

Results of two-factor ANOVAs for the effects of terrain (levels: road, steps) and walking direction (levels: up, down) on gaze (top), eye orientation (middle) and head orientation (bottom). Separate ANOVAs are used for the means of horizontal and vertical eye/head/gaze orientation as well as for the spread (standard deviation) of horizontal and vertical eye/head/gaze orientation. Significant values (at 5 % level) depicted in bold; gray and white boxes separate the 12 individual tests. Note that for none of the ANOVAs, there is any significant interaction between the factors, excluding that choices of setup and analysis that depend on walking direction interfere with the results on terrain-based effects

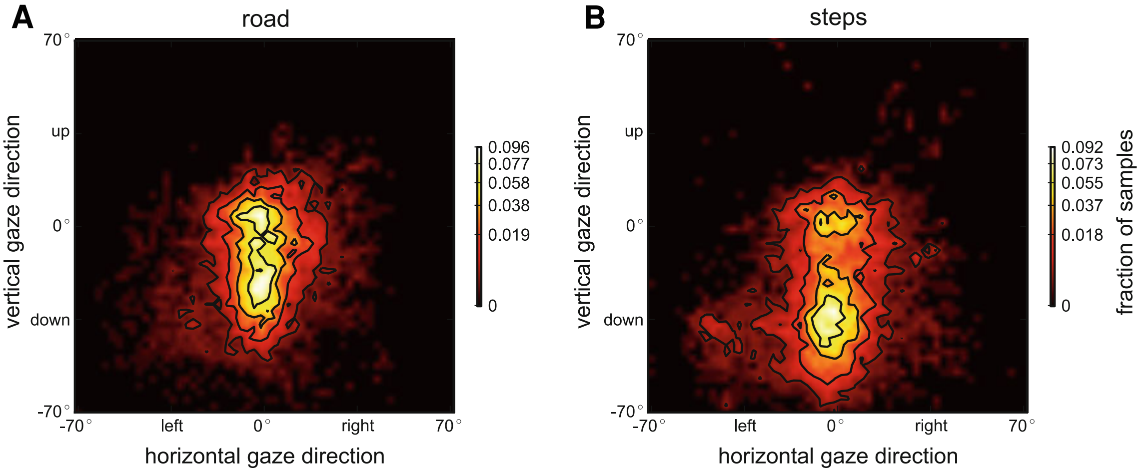

Fig. 2 Gaze-in-world histograms. Histograms of gaze-in-world relative to the vanishing point (2.5° × 2.5° bins, interpolated for display). Note the logarithmic scale for individual panels. *Vertical and horizontal axes* correspond to real space; measurement range is 70° from the center in all directions. *Height lines* correspond to *colorbar ticks*. Data are first averaged per participant, such that each individual contributes equal amounts of data independent of walking speed. **a** road and **b** steps

Taken together, the data on mean and standard deviation show that terrain affects gaze in the vertical direction. The more difficult terrain ("steps") induces lower and more spread gaze than the easier terrain. It is important to note that environments are similar (identical with the exception of a slight change in vantage point) and instructions are identical (with the obvious exception of either walking steps or road), such that all effects result from the interaction of the implicit task set of negotiating terrain with terrain difficulty. The effect of walking direction on horizontal gaze direction, however, might be a consequence of the necessarily different choice of vanishing points for determining head-in-world orientation, which factors into the measure of gaze direction. Both effects raise the question to what extent eye-in-head as compared to head-in-world movements contribute to the observed differences.

Eye-in-head orientation

As one contribution to gaze, we analyze eye-in-head orientation. Visual inspection of the raw distributions shows that the peak of the eye-in-head orientation distribution is higher in the "road" (Fig. 4a) than in "steps" (Fig. 4b) condition. Quantitative analysis (Table 1) shows that the mean horizontal eye-in-head orientation (Fig. 5a) does not depend on terrain or direction, nor is there an interaction between these factors. In contrast, the mean vertical eye-in-head orientation does depend on terrain and walking direction. There is no interaction between terrain and walking direction. While the mean eye-in-head orientation on average is almost on the midline for the road (Fig. 5a), it falls clearly below for steps (Fig. 5b). This shows that terrain difficulty affects vertical eye-in-head orientation in that the more irregular terrain ("steps") demands the eye to be oriented more downwards. That is, with respect to the effects of terrain, eye-in-head orientation shows a similar effect as gaze in full.

To quantify the spread of eye-in-head orientation, we calculate the standard deviation over the vertical and horizontal components of eye-in-head orientation. The standard deviation over the horizontal eye-in-head orientation does not depend on terrain or walking direction, nor is there an interaction between these factors (Fig. 5b). The standard deviation over the vertical coordinates does depend on terrain and is larger for "steps" than for "road". Walking direction does not have an effect on the standard deviation over the vertical eye-in-head orientation, and there is no interaction between terrain and walking direction. Hence, eye-in-head orientation is more spread vertically if terrain gets more irregular. This may imply that there are more or larger eye movements for the irregular terrain, but may also result from longer dwell time in the lower visual field. It should be noted, however, that—unlike in viewing static images in the laboratory—not only saccades contribute to eye-in-head orientation, but also stabilizing and tracking eye movements. The contribution of distinct eye movement classes (slow/fast) will be discussed below (section "Fast and slow eye movements"). In sum, we find robust effects of terrain irregularity on eye-in-head orientation, which are restricted to the vertical direction. This suggests that with increasingly irregular (i.e., more "difficult") terrain, eye movements increasingly direct gaze to the path.

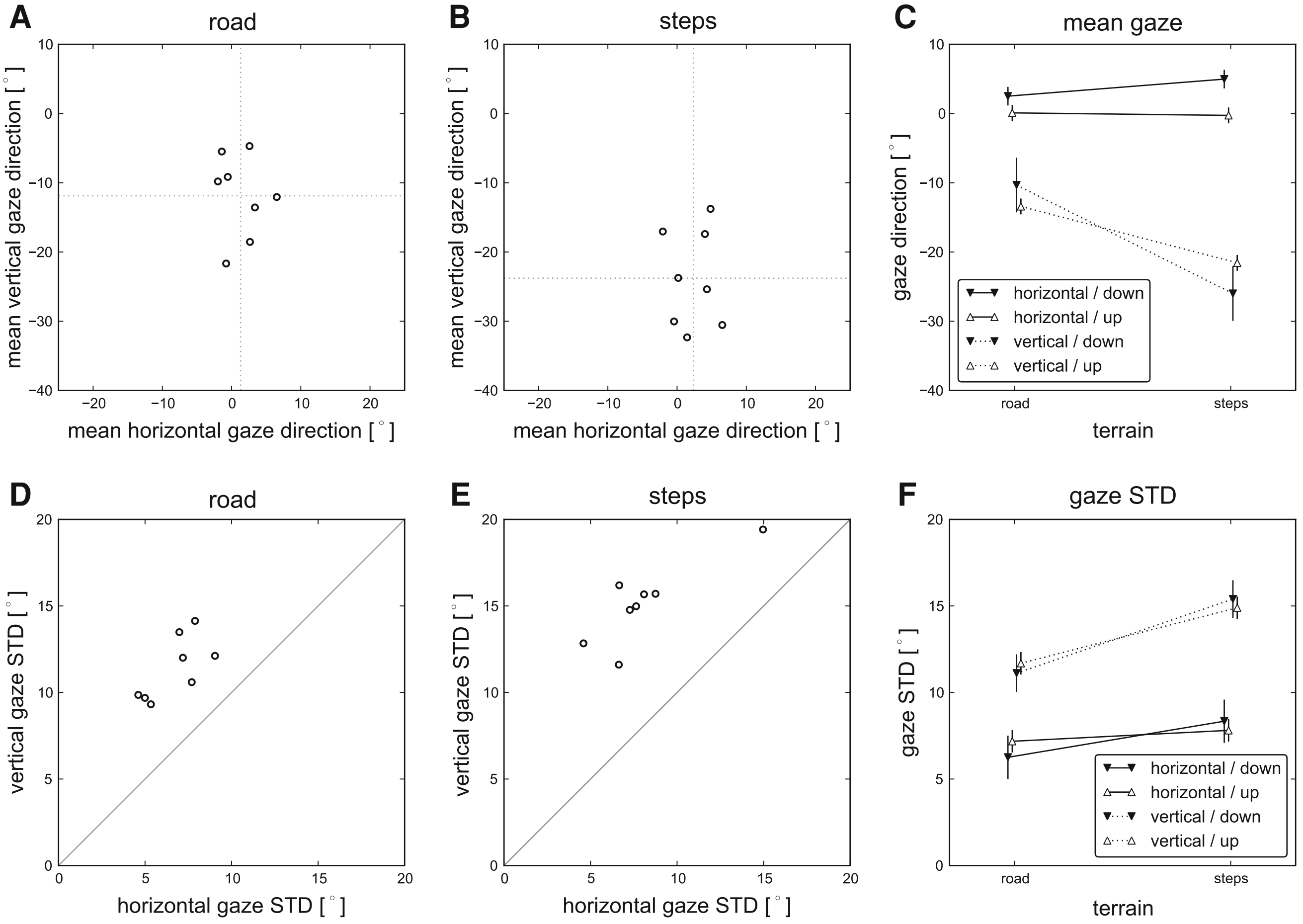

Fig. 3 Gaze-in-world mean and standard deviation. **a** Comparison of the mean *horizontal and vertical* gaze-in-world on the road and steps. *Errorbars* denote standard *errors* of the mean. **b** Comparison of the standard deviations of the *horizontal and vertical* gaze-in-world on the road and steps. *Errorbars* denote standard *errors* of the mean

Effect of environment

Unlike head-in-world orientation and gaze, eye-in-head orientation is independent from the definition of the vanishing point. This allows the comparison to other visual environments. We chose two environments (“alley” and “stairs”), which are similar in terrain regularity to the main conditions (road/steps), but present a different visual environment. Visual inspection of raw distributions of eye-in-head orientations (Fig. 4) indicates that the distribution for steps is more similar to stairs and alley more similar to road than main and control conditions are relative to each other. Since the visual environment and the path inclination change between main conditions and control conditions (and among these), quantitative isolation of terrain’s effect is not possible, which is the key rationale of locating the main conditions in the same environment. Qualitatively, however, the observation that the (visual) environments of alley and stairs are more similar to each other than to the road/steps environment (e.g., with respect to openness) make the data suggest that the effect of terrain may at least partially supersede the effect of environment. In any case, the predominant elongation of eye-in-head orientation distributions along the vertical as compared to the horizontal is present for all environments tested.

Head-in-world orientation

To test whether head-in-world movements are also affected by demands posed by the terrain, we analyze the position of the vanishing point within the head-centered movie frames. From the vanishing point’s position, we determine the head-in-world orientation by inverting the transfer function of the camera. This yields a representation of head orientation in visual angle relative to the vanishing point.

Visual inspection of the raw distributions (Fig. 6) shows that they are shifted more upward for the “steps” as compared to the “road” condition. Since these data are given from the perspective of the head, not the point in the movie frame, they imply that the head points *down*wards in

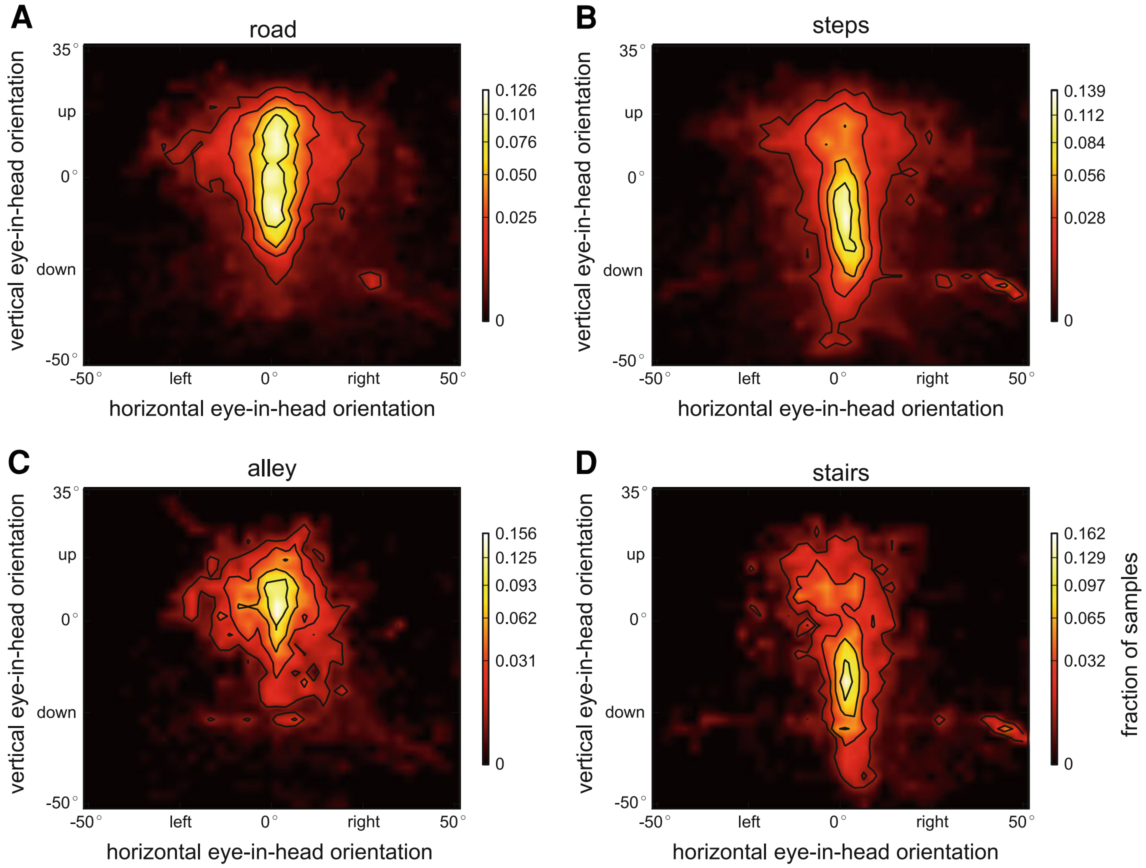

Fig. 4 Eye-in-head orientation histograms. Histograms of eye-in-head orientation (2.5° × 2.5° bins, interpolated for display) Note the logarithmic scale for individual panels. *Vertical and horizontal axes* correspond to real space; measurement range is 35° from the midline toward the top and 50° toward all other directions. Height lines correspond to *colorbar ticks*. Data are first averaged per participant, such that each individual contributes equal amounts of data independent of walking speed. **a** Road, **b** steps, **c** alley, **d** stairs

both conditions, but more downward in the steps condition (Fig. 1c). Abstracting from the way the data are obtained, we hereafter follow the more intuitive convention for "head-in-world orientation", such that "downward" implies the head pointing lower, etc. As for the eye-in-head orientation, we quantify the distribution by the mean head-in-world orientation (Fig. 7a) and the standard deviation over the vertical and horizontal components (Fig. 7b).

We find a main effect of walking direction on the mean horizontal head-in-world orientation (Table 1). There is no effect of terrain and no interaction. For the mean vertical head-in-world orientation, there is an effect of terrain and of walking direction. There is no interaction between the two factors. For standard deviations over the vertical and horizontal head-in-world orientation, there are neither main effects nor interactions for any factor, showing that the head position is kept equally stable in both conditions. The effects of walking direction on mean horizontal head-in-world orientation can likely be attributed to the necessarily different choice of the vanishing point. In contrast, since the environments (and thus the vanishing point choice) are identical for both terrains (within a walking direction), the effect on the vertical component is striking. Head-in-world orientation is lower when walking on the irregular steps than when walking on the more regular road.

So far, we have shown that on the steps the *gaze-in-world* distribution is more elongated than on the road. Separating gaze-in-world into *head-in-world* and *eye-in-head* distributions shows that the differences in gaze distributions are—at least in part—caused by a generally lower head orientation on the steps, which is (over)compensated by a larger vertical spread in eye-in-head position. One hypothesis compatible with this finding is that a lower head is caused by increased terrain difficulty, where the eyes still maintain exploratory or look-ahead behavior. If this is the case, different classes of eye movements should dominate up- and downward movements, respectively: Upward movements should be dominated by saccades (and possibly other fast re-orienting movements), while downward movements should be dominated by reflexive movements and thus be generally slower than upward movements.

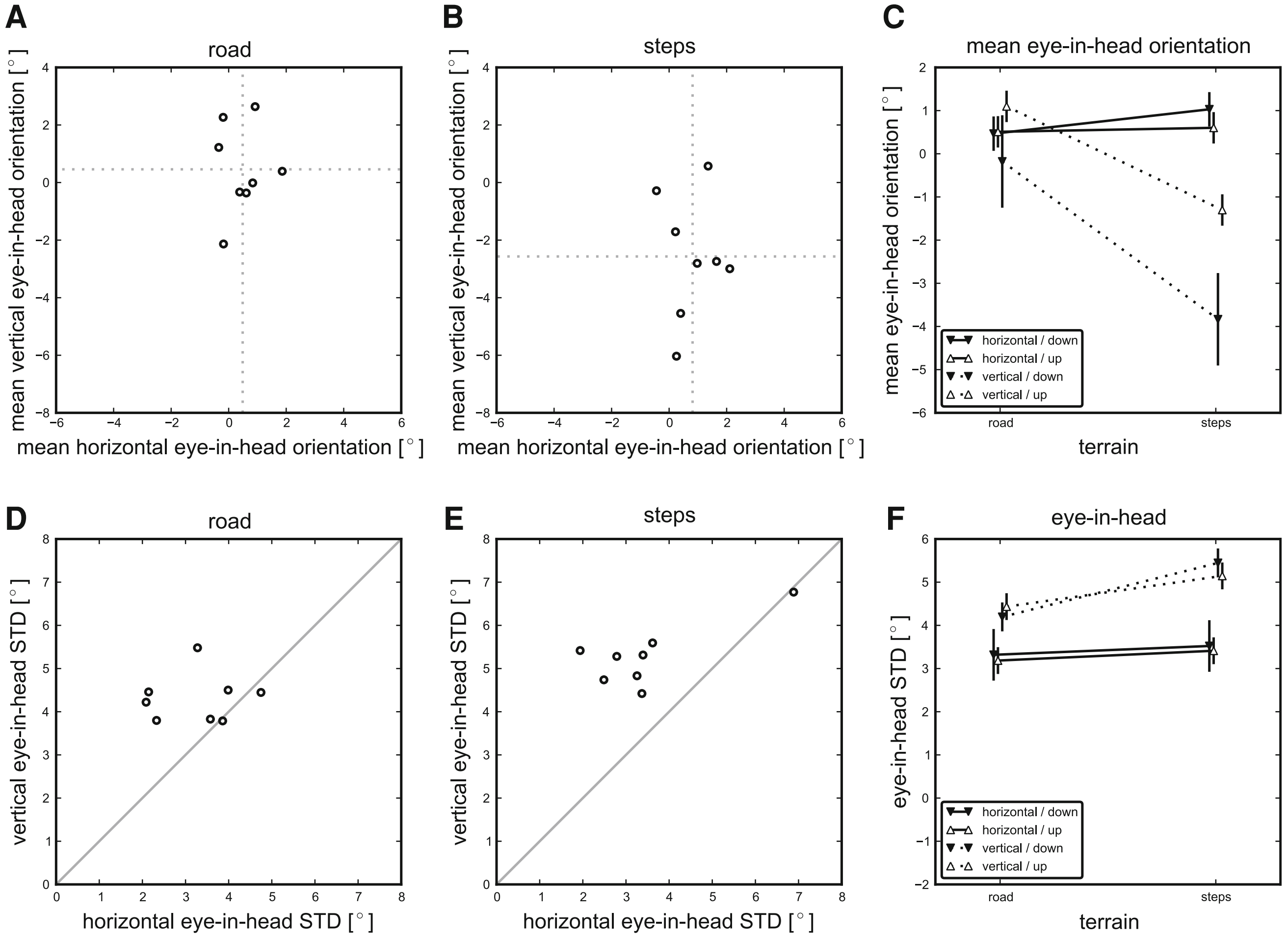

Fig. 5 Eye-in-head orientation mean and standard deviation. **a** Comparison of the mean horizontal and vertical eye-in-head orientation on the road and steps. *Errorbars* denote standard *errors* of the mean. **b** Comparison of the standard deviations of the *horizontal and vertical* eye-in-head orientation on the road and steps. *Errorbars* denote standard *errors* of the mean

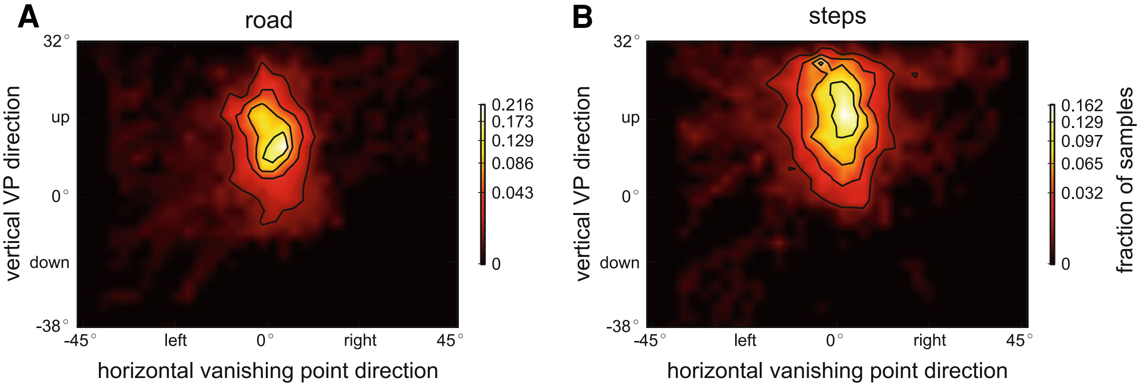

Fig. 6 Vanishing point distributions for head-in-world orientation. Histograms of the vanishing point (VP) directions from the perspective of the head for **a** road and **b** steps (2.5° × 2.5° bins, interpolated for display). Data are first averaged per participant, such that each individual contributes equal amounts of data independent of walking speed. Note that in these raw representations of the data a bin more upward means that the vanishing point is higher and thus the head is pointing lower, etc.

Fast and slow eye movements

The more vertically elongated distribution of gaze-in-world on the steps as compared to the road seems to be caused predominantly by a more vertically elongated distribution of eye-in-head orientation. This implies different patterns of eye movements on the road and on the steps. To address the contribution of slow and fast eye movements to the

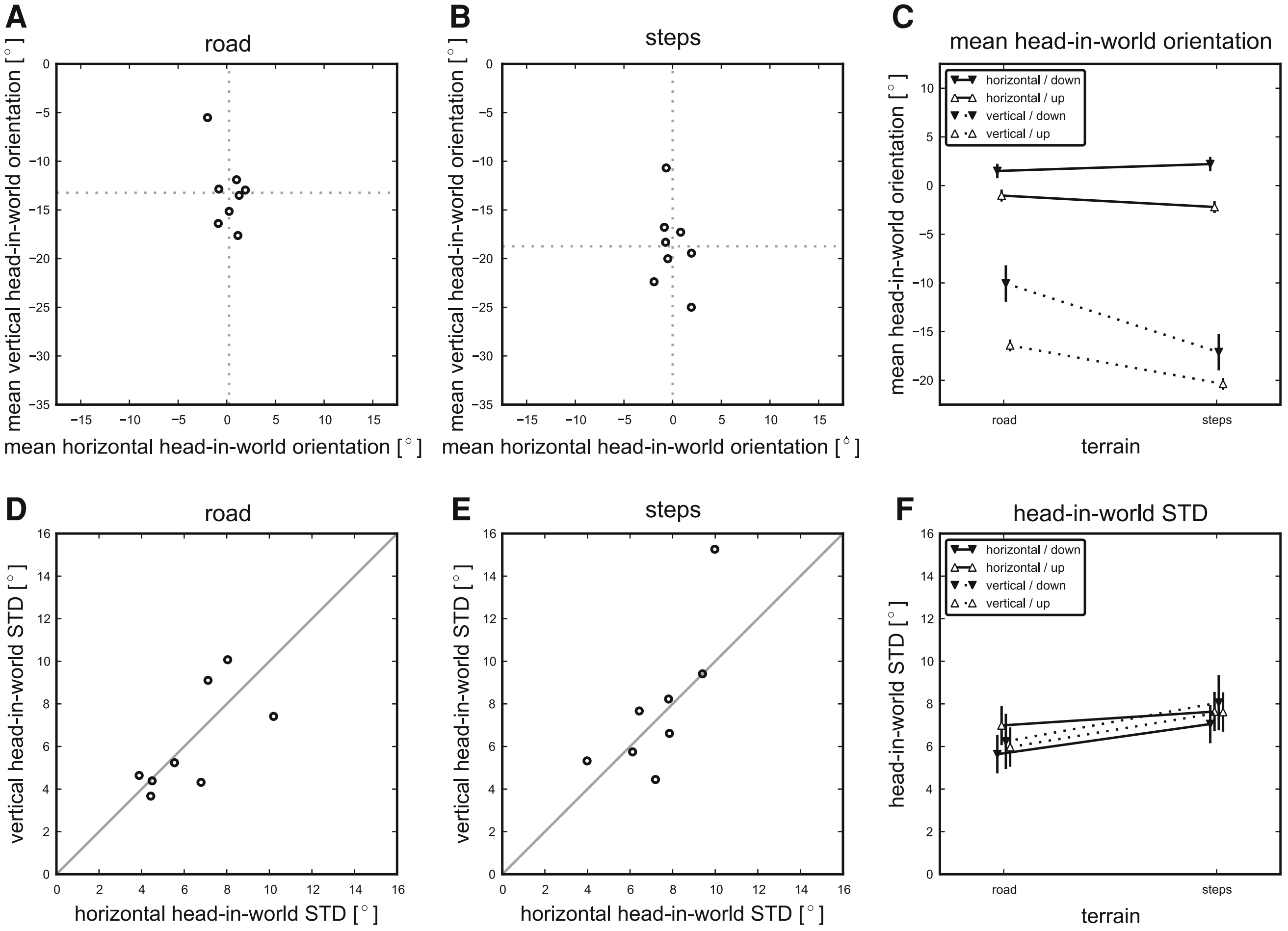

Fig. 7 Head-in-world orientation mean and standard deviation. **a** Comparison of the mean horizontal and vertical head-in-world orientation on the road and on the steps. *Errorbars* denote standard *errors* of the mean. **b** Comparison of the standard deviation of the *vertical and horizontal* head-in-world orientation on the road and on the steps. In all panels, data refer to the head in the world, that is, downward implies the head pointing lower, etc.

direction of gaze on both terrains, respectively, we classify the eye-in-head orientation data based on their speed and compute separate direction and amplitude maps for each speed and terrain (see Methods section "Fast and slow eye movements" for details). Visual inspection of the average direction maps (mean across participants) already indicates that on the road (Fig. 8a, c), slow movements tend to go downward from the upper parts of the eyes' range. In contrast, fast movements tend to originate in the lower part and go upwards. This pattern corresponds to a strategy where points of the terrain are visually tracked while walking toward them and these eye movements are then followed by fast movements to inspect the next point. On the steps, the same pattern is present, and even more pronounced, especially for fast eye movements (Fig. 8b, d).

To quantify this observation, we compare fast and slow movements on each type of terrain within bins containing data of more than half of the participants (i.e., at least 5) in both eye movement types (fast/slow). This is done by performing a Watson–Williams test in each bin, whose results form a pattern that confirms the visual impression (Fig. 8e, f). In 52 bins on the road and 44 bins on the steps, we have sufficient data to compare fast to slow movements. On the steps, 48 % of bins show a significant difference (21/44) in direction between slow and fast movements. In general, as for all bins, fast movements tend to preferentially go up in these significant bins, and slow movements thus preferentially down (Fig. 8a, c). In contrast, only for 1 bin (of 52), there is a significant difference on the road. This is further indication that—although there are similarities in the patterns of eye movements on both types of terrain—the demands imposed by more irregular terrain changes the pattern of eye movements, and more difficult terrain seems to make differences between types of eye movements more pronounced.

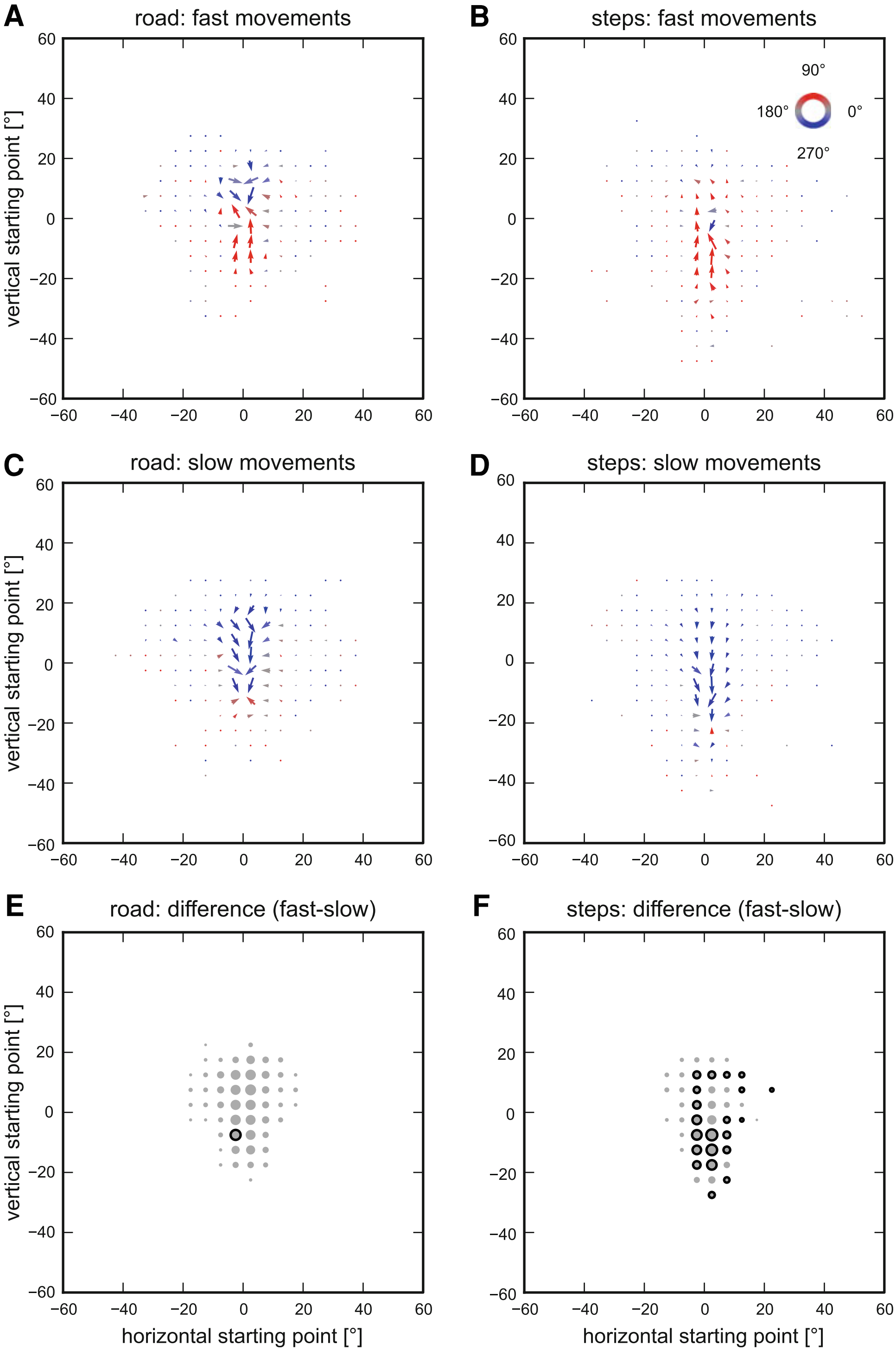

Fig. 8 Spatial organization of eye-movement directions. **a–d** Maps of eye-movement direction sorted by starting point (5° × 5° bins). Direction is given by *color* and (redundantly) by *arrow direction*: *red* movements are *upward* and *blue* movements are *downward*. Length of the *arrows* denotes the amount of total samples contributing to the data in the bin. **a** Fast eye movements on the road. **b** Fast eye movements on the steps. **c** Slow eye movements on the road. **d** Slow eye movements on the steps. **e–f** Statistical comparison of the average directions of slow and fast eye movement within terrain type. *Gray disks* are shown in bins where data from at least 5 participants in each type of eye movement were present and allowed for a test. *Black circles* indicate statistical significance, after correction for multiple comparisons at a 5 % expected false discovery rate (FDR; Benjamini and Hochberg 1995) within each map. The size of *disks* and *circles* reflects the amount of eye movements in the bin. **e** Direction of eye movements on the road. **f** Direction of eye movements on the steps

So far, we have considered eye-movement direction only, irrespective of amplitude. A similar analysis is performed to compare the *amplitude* of eye movements within the two types of terrain irrespective of direction. We do not find any effect of individual bins when comparing the median amplitudes across participants ($p > .063$ in each bin, t test).

In addition to considering maps, we now pool over all starting points to compare direction and amplitude distributions. Besides increasing statistical power for amplitude comparisons, this allows us to directly compare the two types of terrain statistically. First, the distributions of directions of slow as well as fast movements on both the road and steps are represented in a histogram, showing the average proportion of movements in each direction (30° bins). The distributions of the directions of fast and slow movements have different shapes, independent of terrain. However, slow movements on the steps appear to be directed (even) more downward than those on the road (Fig. 9a, b).

The distributions of directions for slow and fast movements are compared with each other for all data, as well as separately for both terrains. Since directions are circular data, a Watson's test for homogeneity is used. The overall distributions of fast and slow movements' directions are different ($U^2 = 8.306$; $p < .001$). The distributions of fast movements differ between the two terrain types ($U^2 = 0.580$; $p < .001$) as do the distributions of slow movements ($U^2 = 4.538$; $p < .001$). All of these results are in line with the spatial organization of eye movement directions ("slow down, fast up").

The size of the downward shift of slow movements on the steps cannot be fully explained by the differences in the distribution of fast movements, as those are relatively small and occur both upward and downward. Consequently, we expect the preference for downward-directed slow movements on the steps to be compensated by eye-movement amplitude changes. Either slow, downward eye movements have smaller amplitudes than slow, upward eye movements on the steps, or fast, upward eye movements have larger amplitudes than fast, downward eye movements. To test this specific possibility, we compared the median amplitude of eye movements directed upward (30° bin centered on 90°) and downward (30° bin centered on 270°) for each participant, separated by terrain and eye-movement speed (Fig. 9c, d). Most notably, on the steps the difference between the amplitudes of upward and downward fast eye movements appears to be larger than the same difference on the road. This is tested with Welch's t tests. The difference between upward and downward fast eye movements is larger on the steps than on the road ($t(11.57) = 2.859$; $p = .014$). We do not observe an effect for slow eye movements ($t(13.813) = -0.318$; $p = .755$).

In sum, eye-in-head orientation and head-in-world orientation are pointed more toward the ground when the terrain is more irregular (and thus more difficult). Only for eye-in-head orientation, the vertical spread is increased for

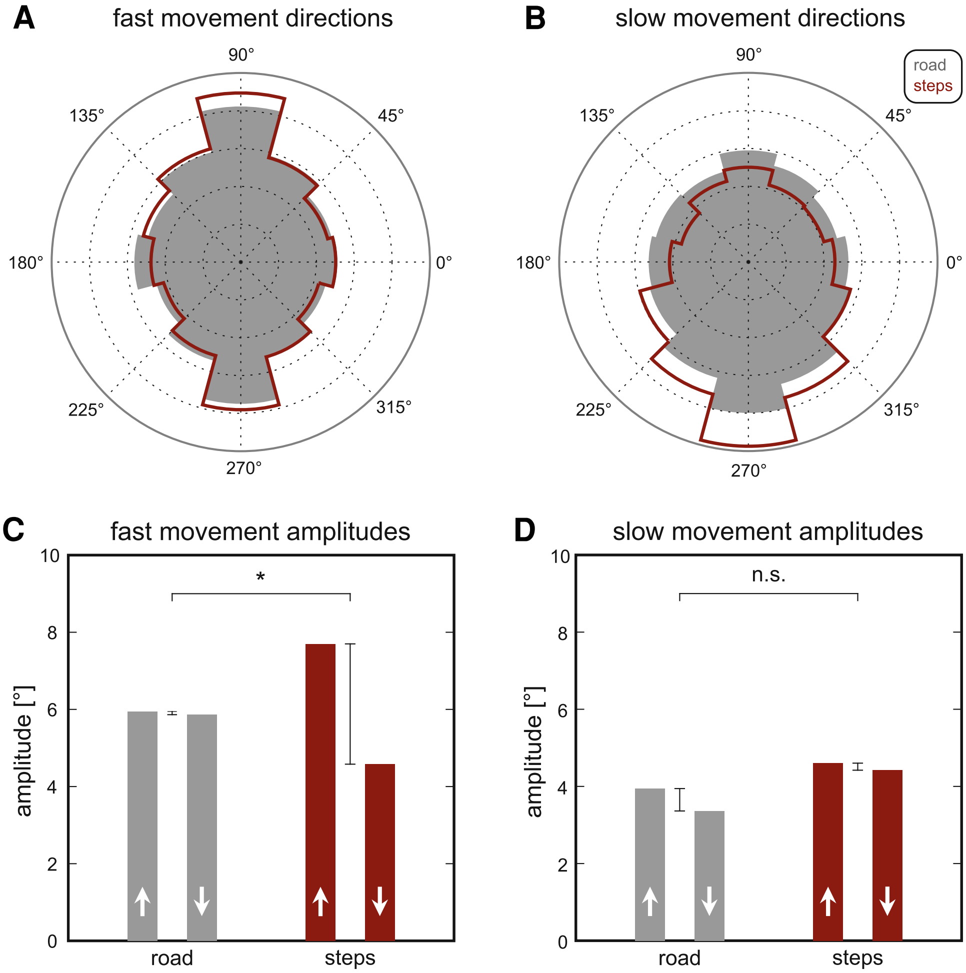

Fig. 9 Overall eye movement directions and amplitudes. Eye movements from the road are represented in *gray*, and eye movements from the steps in *red*. **a, b** Distribution of eye-movement directions as radial histograms, with bins of 30°. The surface area in each directional bin corresponds to the proportion of eye movements falling in that bin. **a** Distributions of directions of fast eye movements. **b** Directions of slow eye movements. **c, d** Median amplitude of upward and downward eye movements (direction indicated by *white arrows*), averaged across observers. The bins—with a width of 30° centered around 90° (*upward*) and 270° (*downward*)—were chosen for further analyses given results of previous analyses. **c** Fast eye movement amplitudes. **d** Slow eye movement amplitudes

the more difficult terrain. This suggests that both eye and head subserve the adjustment of gaze for terrain negotiation. However, while eyes and head are both oriented more downward for more difficult terrain, only the eyes partially compensate for this through more or larger vertical movements. Indeed, the patterns of eye movements on each type of terrain share some similarities, but with more irregular terrain, slow eye movements tend to go downward more often and fast upward eye movements go upwards further. These eye-movement patterns confirm the suggestion raised by the analyses of raw eye-in-head distributions that the use of eye movements is modulated on the two types of terrain. In short, head orientation presumably adjusts gaze according to global task set, whereas the eyes adapt to more immediate demands while still ensuring a gaze component for path planning and exploration of the visual environment.

Discussion

Our study shows distinct effects of terrain on real-world eye and head movements, when all other factors (environment, instructions) are kept constant. Most likely as an adjustment to terrain regularity, gaze is distributed differently on the two types of terrain. The contributions of eye-in-head orientation as compared to head-in-world orientation to gaze are found to be complementary. Both serve to point gaze lower when terrain gets more irregular (i.e., more difficult), while only eye movements are adjusted to maintain some exploratory gaze to the upper part of the visual field. This is achieved by adapting eye movement patterns to terrain irregularity. These results are in line with real-world observations made previously (Land et al. 1999; Pelz and Rothkopf 2007) and may serve as real-world validation of previous laboratory experiments (e.g., Hollands et al. 2004; Marigold and Patla 2008).

Qualitatively, the lower peak in the distribution of gaze on the steps appears to contain a larger portion of the samples as the same peak on the road. This may indicate that gaze is not only directed lower, but also remains so for longer when people negotiate more irregular terrain. A possible explanation is that the latency from eye movement to footfall is increased, as has been observed before (Chapman and Hollands 2006b). It has been suggested that this reflects the time needed to plan a step (DiFabio et al. 2003), which may on average be longer on irregular terrain. In a manual task, the latency between shifts of gaze and hand movements increases when objects had to be moved instead of only touched (Smeets et al. 1996). Additionally, the latency of head movements relative to shifts of gaze decreases when hand movements are to be made. Such changes in the latencies of different movements may partially explain the differences in the gaze distributions observed here. Namely, gaze is lowered longer before a footfall on the steps in comparison with footfalls on the road, to allow for more planning time. This would cause a larger portion of the gaze to be directed at the path on the steps as compared to the road. It is important to note that the present study is not intended to address the visual control of walking *per se*, but rather uses walking as a means to implicitly manipulate task. Nonetheless, measuring gait parameters together with gaze and head orientation under natural conditions is likely to eventually complement laboratory studies in addressing the multifaceted interactions of eye, head and body during walking.

The observed effects of walking direction may be explained in part by the difference in reference point and in part by the slant of the path itself. While the main effects of walking direction therefore have to be interpreted with care, the absence of an interaction between walking direction and terrain verifies the robustness of the terrain effects against walking direction, and thus against walking speed, physical effort and any potential left–right bias in the chosen visual environment.

Interestingly, a strong predominance of head movements to allocate gaze to task-relevant points is observed in driving, when a highly experienced driver is negotiating a familiar track (Land and Tatler 2001). In this situation, eye movements get decoupled from head movements, and only head movements are strongly coupled to a specific task-relevant variable. This decoupling seems to be a consequence of experience as it is not observed in a non-professional driver on a non-overtrained road (Land 1992). Given that our observers as healthy adults have a lifetime of experience with walking (though not on the particular track used), the relative flexibility of the eyes relative to the head is in line with these data.

Not only do head-in-world and eye-in-head orientations contribute differently to a task-relevant adaptation of gaze, but the contributions of fast and slow eye movements are also different on the two terrain types. Despite the fact that participants were in no way constrained to look at the path and were presented with a lively natural environment to explore, we could still distinguish differences in how fast and slow eye movements were used on both terrain types. In general, slow movements appear to be used to inspect specific locations on the terrain, whereas fast eye movements serve to direct gaze upwards again. With increasing terrain irregularity, this distinction is more clearly visible, suggesting again that a single strategy for gaze allocation, involving eye movements as well as head orientation, is adapted to immediate demands in every-day tasks such as walking.

One of the few studies that have investigated the relation between bodily orientation and eye-in-head movements on gaze allocation in a naturalistic task found that both the onsets and offsets of whole body movements precede those visual fixations of the task-relevant object, which in turn precede those of manipulation of the object (Land et al. 1999). This contrasts with data obtained in a more artificial, visually reduced setting, where eye movements can precede head and body movements, although an equally tight link between these movements is observed (Hollands et al. 2004). Highlighting the importance of naturalistic settings, our finding that humans orient themselves in a generic way to the terrain by adjusting their head orientation is in line with Land et al. (1999) data. Depending on instantaneous terrain demands, such as the steps in this task, eye-in-head orientation is spread out to gather specific information necessary for immediate action. Hence, the role of head movements is limited to infrequent and coarse reorientations—which were apparently largely absent in this task—whereas eye movements serve to refine gaze for immediate informational demands. In this respect, our data are a first step to transfer the data obtained under rather constrained conditions (sports, food preparation, laboratory walking tasks) to a (nearly) unconstrained environment with a real-world activity.

As the relationship between step cycle and eye movements indicates (Hollands and Marple-Horvat 1996; Chapman and Hollands 2006a), it is likely that eye movements are an integral part of skilled behavior, probably embedded in visuomotor routines established over many years of experience with walking on streets. By combining our approach of unconstrained, natural behavior with systematically varied terrain difficulty and enforced or instructed eye-movement behaviors (e.g., by dynamically blocking certain parts of the visual field), it is well conceivable that adaptation of task-set-specific eye-movement behavior to experience can be assessed also under natural conditions and for prolonged periods.

Besides varying the difficulty of terrain as we do here, the demands walking imposes on gaze direction may also be affected by various neurological conditions. Parkinson's disease and related syndromes, in which walking is severely impaired and performance in eye-movement tasks serves as clinically relevant marker (Corin et al. 1972; Van Koningsbruggen et al. 2009; Pinkhardt et al. 2008), exemplify this relation of concurrent impairment of gaze and gait. Treating oculomotor symptoms, in turn, can lead to improvements in walking during daily living, at least in a Parkinsonian syndrome associated with severe oculomotor impairment (Zampieri and Di Fabio 2008). A better understanding of the roles of eye, head and body for the allocation of gaze during walking under conditions of varying difficulty may thus also eventually be of relevance for clinical applications (Marx et al. in press).

It is long known that task affects eye movements (Buswell 1935; Yarbus 1967) and can override stimulus-related signals robustly (Henderson et al. 2007) and immediately (Einhäuser et al. 2008). Similarly, context and environment influence gaze allocation (Torralba 2003; Ehinger et al. 2009). In our main conditions ("road", "steps"), we held all these variables constant and only had the implicit task set given by terrain negotiation varied. The rich, multisensory input experienced when performing a comparably simple task, walking 55 m of inclined cobblestone, can hardly be mimicked in the lab. In turn, the real world's complexity comes at the cost that it is virtually impossible to measure, let alone control, all parameters that are of potential relevance. Hence, laboratory measurements and real-world experiments complement each other: When observing differences between lab and reality, the differences need to be quantified, candidate parameters isolated, manipulated, and then again the results have to be validated in the real world. In the context of gaze research, only very recently—with the advent of wearable eye tracking—this has become technologically feasible, and laboratory results from decades of research can now be tested for their ecological validity in rather unrestrained settings ('t Hart et al. 2009; Cristino and Baddeley 2009; Droll and Eckstein 2009). Measuring the effects of comparably simple manipulations (as road vs. steps) in the real world is a crucial first step in this research program to complement laboratory research. Eventually, this research program will allow quantifying the extent to which theoretical models and experimental results remain applicable outside very constrained laboratory settings.

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