

Gaze behaviour during space perception and spatial decision making

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Abstract A series of four experiments investigating gaze behavior and decision making in the context of wayfinding is reported. Participants were presented with screenshots of choice points taken in large virtual environments. Each screenshot depicted alternative path options. In Experiment 1, participants had to decide between them to find an object hidden in the environment. In Experiment 2, participants were first informed about which path option to take as if following a guided route. Subsequently, they were presented with the same images in random order and had to indicate which path option they chose during initial exposure. In Experiment 1, we demonstrate (1) that participants have a tendency to choose the path option that featured the longer line of sight, and (2) a robust gaze bias towards the eventually chosen path option. In Experiment 2, systematic differences in gaze behavior towards the alternative path options between encoding and decoding were observed. Based on data from Experiments 1 and 2 and two control experiments ensuring that fixation patterns were specific to the spatial tasks, we develop a tentative model of gaze behavior during wayfinding decision making suggesting that particular attention was paid to image areas depicting

changes in the local geometry of the environments such as corners, openings, and occlusions. Together, the results suggest that gaze during a wayfinding tasks is directed toward, and can be predicted by, a subset of environmental features and that gaze bias effects are a general phenomenon of visual decision making.

Keywords Visual attention · Wayfinding · Decision making · Gaze behavior · Spatial cognition · Space perception

Introduction

Where do we look when moving through the environment? In the context of navigation and wayfinding, eye-tracking studies have primarily investigated the role of gaze for the control of locomotory or steering behavior. Wayfinding, however, also comprises higher level processes such as encoding information into and retrieving it from spatial memory, path planning, and decision making at choice points. So far, very few eye-tracking studies investigated these processes to answer questions like: how does gaze behavior relate to spatial decision making? Is it possible to predict path choices by analyzing gaze behavior? And, which information are attended to when interpreting spatial situations and deciding between path alternatives? This work constitutes a first account to approach these questions.

Gaze behavior and navigation

Gaze behavior has been investigated in studies that required participants to move through space. Grasso, Prevost, Ivanenko, and Berthoz (1998) demonstrated anticipatory gaze behaviour when walking along curved paths. Similar results

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59 also come from steering experiments: when driving a car
60 around a curve, drivers gaze at the tangent point on the
61 inside of the curve (Land & Lee, 1994; Land & Tatler,
62 2001). Moreover, steering performance systematically
63 decreases if gaze is fixed (Wilkie & Wann, 2003), and is
64 biased in the direction of gaze (Reader, Chatziastros,
65 Cunningham, Bühlhoff, & Cutting, 2002). Gaze behavior
66 while moving through space has also been investigated in
67 tasks involving navigation through cluttered spaces con-
68 taining large objects (Rothkopf, Ballard, & Hayhoe, 2007).
69 Fixation patterns were task specific, systematically differing
70 when participants were asked to approach the objects and
71 when asked to avoid them. In all these studies, participants
72 solved prototypical locomotion tasks, such as steering,
73 obstacle avoidance and approach, that require moving
74 through the world in response to sensory-motor input of the
75 local surrounding.

76 Montello (2001) conceptually separates navigation
77 behavior into locomotion and wayfinding. Locomotion
78 refers to navigation behavior in response to current sen-
79 sory-motor input of the immediate surroundings and is
80 therefore strongly related to the act of physically moving
81 through space. Wayfinding tasks, in contrast, aim at reach-
82 ing destinations beyond the current sensory horizon and
83 involve some representation of the environment, decision
84 making and/or planning processes. These processes,
85 although crucial for successful wayfinding and navigation,
86 are not necessarily tied to the act of physically moving
87 through space. Typical wayfinding tasks are search, explo-
88 ration, route learning, and route planning. Wiener, Büchner,
89 and Hölscher (2009) analyze the level of information
90 required for different wayfinding tasks and show that in
91 many cases knowledge about key choice points and their
92 connectivity is sufficient.

93 The question of how gaze behavior relates to wayfind-
94 ing-related tasks such as memorizing and recalling path
95 choices and movement decisions along a route, or deciding
96 between path alternatives at junctions when exploring
97 novel environments, has been addressed only in very few
98 studies. Schuchard, Connell, and Griffiths (2006) collected
99 eye-tracking data with dementia patients navigating the
100 hallways of a nursing home. These patients showed a lack
101 of ability to attend to wayfinding-critical cues (like signage)
102 predominantly focussing on the lower parts of their visual
103 field, presumably concentrating on motion control issues
104 (i.e., the locomotion-component of navigation). Vembar
105 et al., (2004) employed eye-tracking techniques to capture
106 visual attention while wayfinding in a virtual reality (VR)
107 maze. Their data analysis is limited to the relative amount
108 of time spent looking at the 3D environment versus a sup-
109plementary survey map of the same environment. Spiers
110 and Maguire (2008) present eye-tracking evidence on taxi
111 drivers' pattern of visual attention in a VR driving simulation

112 of London. Finally, Allen and Kirasic (2003), using a slide-
113 show paradigm similar to the one applied in the present
114 study, identified difference in visual focus between scenes
115 with high versus low density of wayfinding-critical cues.
116 Neither of these studies identified how eye movements
117 relate to deciding between route options and analyzed
118 which specific geometric features of the environment were
119 attended when doing so.

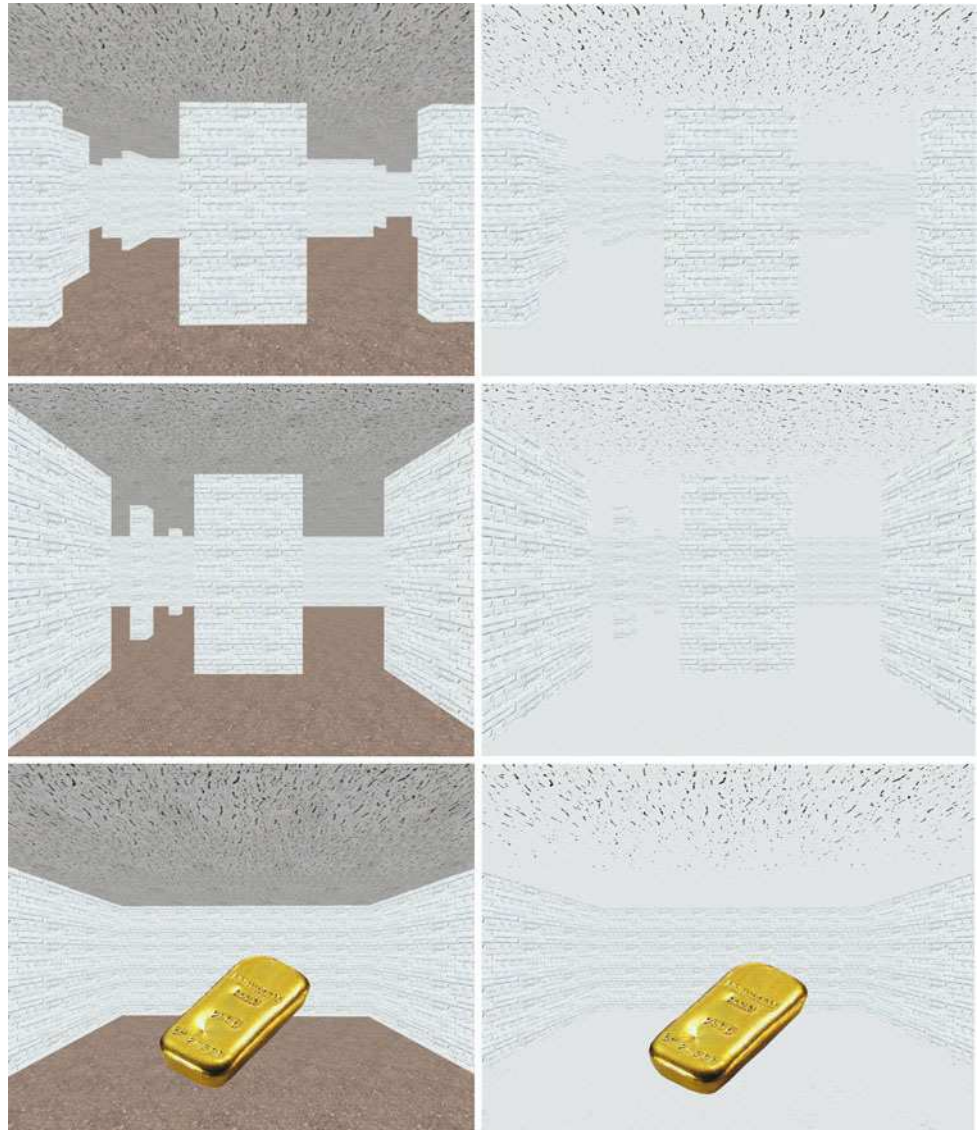
120 The relation between decision making and gaze behavior
121 has been studied in non-spatial contexts, and has been
122 shown to be closely tied to preferences (e.g., Simion &
123 Shimojo, 2007; Armel, Beaumel, & Rangel, 2008). Shim-
124 ojo, Simion, Shimojo, and Scheier (2003) demonstrated
125 that participants when asked to select the most attractive
126 face, display a stable gaze bias towards the eventually cho-
127 sen face in the last second before reporting the decision.
128 The *gaze-cascade model* states that gaze is not merely
129 reflecting preferences, but is involved in the formation of
130 preferences. Essentially, it suggests that gaze orientation
131 towards a stimulus and preference for that stimulus are
132 linked in a positive feedback loop. Glaholt and Reingold
133 (2009) recently extended these findings by demonstrating
134 that the gaze bias effect is not specific for preference
135 choices but constitutes a more general phenomenon of
136 visual decision making. However, up to now it remains an
137 open question whether similar effects can also be observed
138 in spatial decision making when deciding between path
139 alternatives. This question will be approached in the current
140 study.

Control of visual attention 141

142 Currently, it is also unknown which characteristics of the
143 environment viewers are attending to when deciding
144 between path alternatives in the context of wayfinding. The
145 features people attend to when inspecting images of scenes
146 in a non-spatial context, in contrast, have been investigated
147 in numerous studies revealing bottom-up as well as of top-
148 down influences (for an overview see Henderson, 2003).
149 *Bottom-up approaches* state that certain features of a visual
150 scene attract attention and result in shifts of attention. The
151 most widely used bottom-up approach is that of saliency
152 maps, representations of the stimulus coding the strength of
153 different features that are known to be extracted in early
154 vision such as color, intensity and orientation (Itti & Koch,
155 2000, 2001; Parkhurst, Law, & Niebur, 2002; Foulsham &
156 Underwood, 2008). The *Contextual Guidance Model* of
157 attention (Torralba, Oliva, Castelhana, & Henderson, 2006)
158 extends pure bottom-up approaches by acknowledging that
159 both context and task modulate the selection of image
160 regions that are attended to. Generally, *top-down*
161 *approaches* focus on task-related influences on gaze con-
162 trol. For example, gaze patterns when inspecting the same

163	image systematically differ when judging the ages of people	214
164	depicted or when estimating their material circumstances	215
165	(Yarbus, 1967), and fixation patterns differ when viewers	216
166	search for an object in a scene or when they are memorizing	217
167	that scene. (Henderson, Weeks, & Hollingworth, 1999;	218
168	Castelhano, Mack, & Henderson, 2009). In general, top-	219
169	down approaches state that humans use their knowledge	220
170	about the world or the task at hand to guide their fixations	221
171	when inspecting sceneries (Henderson, Malcolm, &	222
172	Schandl, 2009).	223
173	In the context of a wayfinding task in which participants	224
174	have to decide between path alternatives, top-down influ-	225
175	ences would suggest that attention is directed to stimulus	226
176	areas that convey information about the spatial structure of	227
177	the visible space. This opens up the intriguing question of	228
178	whether it is possible to relate a wayfinder's visual attention	229
179	to purely geometrical properties of the depicted space.	230
180	Synopsis	231
181	Two questions shall be considered in this study: (1) how	232
182	does gaze behavior relate to spatial decision making? Are	233
183	participants' choices reflected by gaze bias effects? (2) How	234
184	does control of visual attention in spatial decision making	235
185	relate to stimulus characteristics? Is it possible to predict	236
186	gaze behaviour by analyzing geometric features of the spa-	237
187	tial scenes? Question 1 is addressed with two psychophys-	238
188	ical experiments in which participants were presented with	239
189	images taken at choice points in large, complex virtual	240
190	mazes, each depicting path alternatives. Their task in	241
191	Experiment 1 was to select between the alternatives in	242
192	order to search for an object that was hidden in the environ-	243
193	ment. In Experiment 2 participants were instructed about	244
194	which path alternative to choose in an encoding phase. In	245
195	the subsequent decoding phase, they had to recall these	246
196	choices. In order to address how gaze behaviour relates to	247
197	spatial decision making, we calculate the likelihood that the	248
198	eventually chosen path option is inspected as a function of	249
199	time.	250
200	We then address the question of whether gaze behaviour	251
201	during wayfinding decision making can be predicted by	252
202	purely geometric features of the stimuli. First, two control	253
203	experiments are presented to ensure that the fixation pat-	254
204	terns in Experiments 1 and 2 were in fact task specific. We	255
205	then relate participants' fixation patterns to quantitative	256
206	descriptions of the geometry of the depicted scenes and	257
207	compare the predictive power of different geometrical char-	258
208	acteristics for the recorded fixation patterns.	259
209	Note that the present study was not designed to investi-	
210	gate the role of sensori-motor information or of allocentric,	
211	metrically embedded survey representations for navigation.	
212	Authors like Zetsche, Galbraith, Wolter, and Schill (2009)	
213	argue that weaker representation of environments such as	
	route-level knowledge about landmarks and connections	214
	between them (cf. Siegel & White, 1975), are often suffi-	215
	cient for successful wayfinding (see also Gillner & Mallot,	216
	1998). For the given tasks this is in line with a taxonomic	217
	account recently presented by the authors (Wiener et al.,	218
	2009). The static images of wayfinding decision points in	219
	this paper do not provide the participants with information	220
	about the Euclidean distance or angle between the snap-	221
	shots, as would be obtained from actual movement through	222
	space and as would be necessary for path integration or	223
	determining novel routes/shortcuts between destinations.	224
	Yet the stimuli do provide information about the potential	225
	environmental structure beyond the current view (line of	226
	sight and number of occlusions suggesting further path	227
	options, cf. Peponis, Wineman, Rashid, Kim, & Bafna,	228
	1997) as well as unique local layout (structural landmarks,	229
	see Stankiewicz & Kalia, 2007). The current study investi-	230
	gates the influence of these factors on wayfinding decision	231
	making. Untangling the impact of sensori-motor informa-	232
	tion and correct metric knowledge about relations between	233
	decision points will be an issue of future research.	234
	Experiment 1	235
	Methods	236
	<i>Participants</i>	237
	Twenty subjects (14 women, mean age 22.45 ± 2.83 years)	238
	participated in the experiment. They were mostly university	239
	students and were paid 8 Euros an hour.	240
	<i>Stimuli</i>	241
	The stimuli were 30 screenshots from within large virtual	242
	architectural environments (for examples, see Fig. 1). Each	243
	screenshot was taken at a decision point, depicting two path	244
	options. Pilot experiments suggested that stimuli as	245
	depicted in the left column of Fig. 1 could be compre-	246
	hended without many gaze shifts. This observation is in	247
	line with literature suggesting that a coarse interpretation of	248
	a scene can be computed without the need for selective	249
	visual attention (Oliva & Torralba, 2006). However, one	250
	goal of this study was the investigation of which environ-	251
	mental features are crucial for the comprehension of the	252
	spatial structure of the depicted scenes (space perception)	253
	and for wayfinding decision making. We therefore manipu-	254
	lated the stimuli by selectively adjusting the colors of floor	255
	and ceiling to that of the walls (compare left and right col-	256
	umn in Fig. 1) such that the geometry of the depicted scene	257
	could not be comprehended without overt shifts of atten-	258
	tion. While this manipulation allowed us to monitor which	259

Fig. 1 *Left column* un-manipulated stimuli; *right column* manipulated, experimental stimuli used for the study; *upper and middle row* two examples of decision points presented to participants; *lower row* the final stimulus presented at the end of each search, demonstrating that participants have found the hidden item (*the gold bar*)

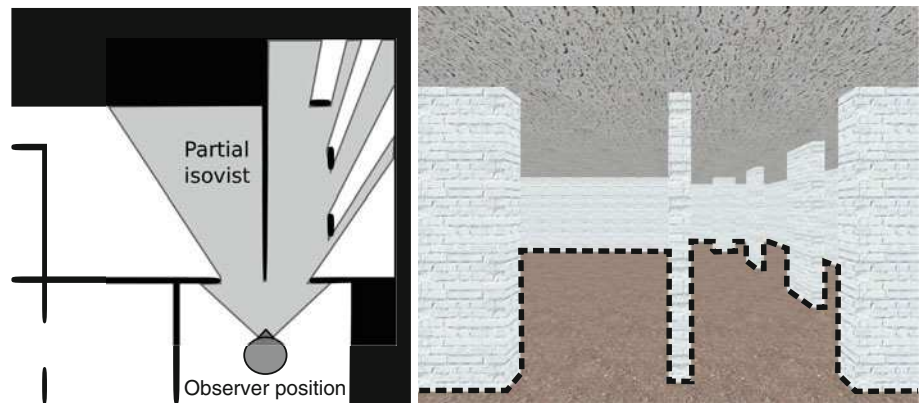


260 environmental features participants attended to by recording
 261 ing eye-movements, one may argue that as a result of this
 262 manipulation it is unclear if, and how, findings from this
 263 study apply to more natural settings. In real life, however,
 264 we also make wayfinding decisions under bad lightning
 265 conditions and scenes cover much larger portions of the
 266 visual field than in our experiments. Under these conditions
 267 viewers will often not be able to comprehend the structure
 268 of the scene in a single glance only and will need to shift
 269 attention overtly. We assume that such attention shifts in
 270 real-world wayfinding will be directed to similar environ-
 271 mental properties as in the current study.

272 For the sake of clarity, further figures will depict the
 273 unmanipulated stimuli. Two versions of each stimulus were
 274 generated by mirroring the original stimulus along the ver-
 275 tical axis. Presentation of the original and the mirrored
 276 stimuli was balanced between participants.

277 *Spatial analysis* For analysing spatial characteristics of
 278 small-scale environments isovists have been suggested as
 279 objectively determinable basic elements (Benedikt, 1979).
 280 Isovists capture relevant spatial properties by describing the
 281 visible area from a given observation point with the use of
 282 viewshed polygons. The spatial characteristics of the scenes
 283 in this study were analyzed using a variant of isovist analy-
 284 sis: for each stimulus a depth profile was generated by con-
 285 touring the edge between the floor and the walls (see Fig. 2
 286 right). The height of the resulting contour describes the
 287 geometry of visible space by the distances of the vertical
 288 walls from the observer. Areas in the stimuli in which the
 289 profile is high relate to areas in space that are distant and
 290 vice versa. This analysis was chosen, because (1) the spatial
 291 situation is described from the perspective of the beholder
 292 capturing behaviorally relevant properties of space (Wiener
 293 et al., 2007; Franz & Wiener, 2008); (2) the visual system is

Fig. 2 *Left* Position in the maze from which one of the snapshots was taken. The *grey* area represents the isovist (depth profile) at this position; *right* corresponding view in the ego-perspective. The depth profile that is approximated by the *dashed line* is functionally equivalent to the partial isovist displayed on the *left*



294 able to use functionally equivalent information (i.e., angu- 331
 295 lar declination) for distance judgments (Ooi, Wu, & He, 332
 296 2001); (3) recent approaches in computational vision dem- 333
 297 onstrate that this information can also be computed directly 334
 298 from the image, even for complex natural outdoor scenes 335
 299 (Hoiem, Efros, & Hebert, 2007). The depth profiles were 336
 300 used to compare spatial properties of the left and right path 337
 301 alternative (left and right half of the stimulus). Earlier 338
 302 research suggests that line of sight (Conroy Dalton, 2003) 339
 303 and the local spatial complexity (Wiener et al., 2007) influ- 340
 304 ence navigation and wayfinding behavior. Accordingly, we 341
 305 calculated longest line of sight for both path alternatives as 342
 306 well as the number of straight line segments to approximate 343
 307 their the spatial complexity. In order to verify the complex- 344
 308 ity measure, 12 volunteers, unaware of the experiment and 345
 309 its hypothesis, were asked to rate the stimuli according to 346
 310 their complexity on a scale from 1 to 7. The rated complex- 347
 311 ity for the different stimuli was highly correlated with the 348
 312 total number of straight line segments in the depth profiles 349
 313 ($r = 0.88, p < .001$). 350

314 Procedure

315 Participants first read a description of the experiment stat- 351
 316 ing that their task was to search for an object (a gold bar) 352
 317 that was placed somewhere in the environment. They 353
 318 would be presented with a series of single choice points 354
 319 depicting alternative path options separated by a wall in the 355
 320 middle of the image. Their task was to decide between the 356
 321 left and the right path option. Participants were given no 357
 322 information about where to find the target object. Instead of 358
 323 actually walking through the environment they would then 359
 324 be presented with the next choice point that they would 360
 325 have encountered if actually navigating through the envi- 361
 326 ronment. In order to illustrate this procedure, participants 362
 327 were presented with a series of snapshots taken between 363
 328 two neighboring choice points, as well as an image of the 364
 329 target. By presenting static images, the current study sepa- 365
 330 rates decision making and memory-related processes that

are crucial for successful wayfinding from processes related 331
 to experiencing continuous motion and controlling locomotion 332
 (cf. Montello, 2001; Wiener et al., 2009). 333

334 Before presenting a novel stimulus, participants fixated a 335
 336 small cross in the center of the screen and pressed the 337
 338 'Space' bar. In order to indicate their path choice, they 339
 340 pressed the left or right cursor key. Each stimulus was pre- 341
 342 sented for 5 s, irrespective of when participants responded. 342
 343 In contrast to the instructions participants received, their 343
 344 path choices (left or right) at single choice points had no 344
 345 influence on the image presented next. The images were 345
 presented in random order. The experiment was divided 346
 into 5 routes containing 4, 5, 6, 7, and 8 decisions. After the 347
 last decision, participants were presented with an image of 348
 a gold bar hovering in a small room (see Fig. 1). 349

346 Apparatus

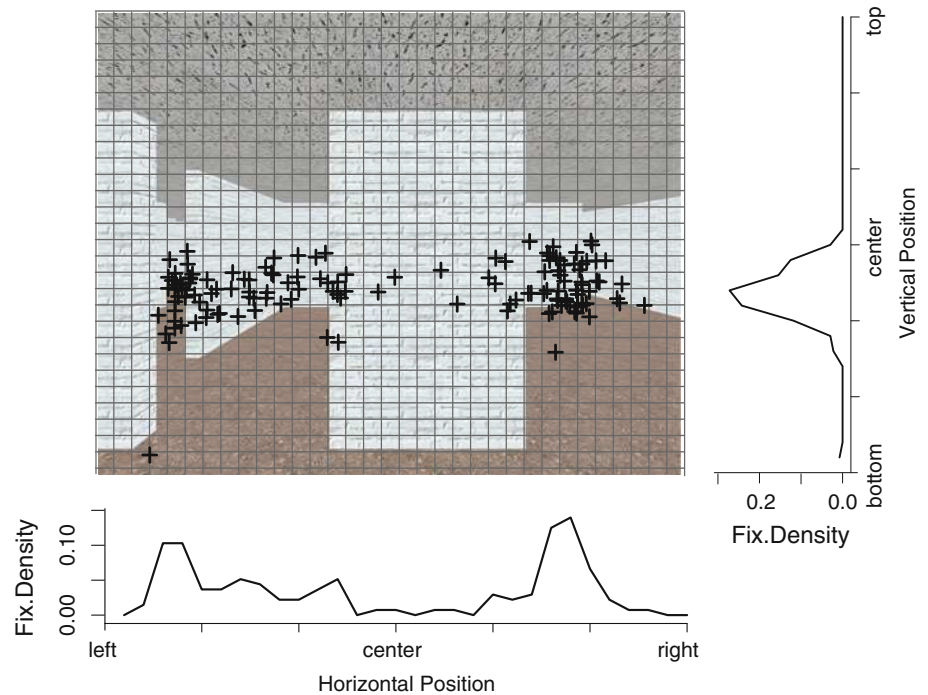
347 The stimuli were displayed at a resolution of $1,024 \times 768$ 347
 348 pixels on a 20" CRT monitor. The screen refresh rate was 348
 349 100 Hz. Participants sat in front of the monitor at a distance 349
 350 of 60 cm, such that the resulting visual angle of the stimuli 350
 351 displayed was 37° (horizontally) \times 28° (vertically). Eye 351
 352 movement were recorded using a SR Research Ltd. Eye- 352
 353 Link II eye-tracker, sampling pupil position at 500 Hz. The 353
 354 Eyelink II eye-tracker is a head-mounted system that does 354
 355 not require the participant's head to be constrained. The 355
 356 eye-tracker was calibrated using a 9-point grid. Fixations 356
 357 were defined using the detection algorithm supplied by SR 357
 358 Research. 358

359 Analysis

360 *Behavioral data* For each stimulus presented, the partici- 360
 361 pants' decisions (left/right) as well as the corresponding 361
 362 response time was recorded. 362

363 *Eye movement data* For each stimulus three *interest* 363
 364 *areas*, vertically dividing the image in to a left part, a central 364

Fig. 3 Exemplary fixation pattern for one of the stimuli. Fixation densities are calculated separately for the horizontal and vertical image dimension



part, and a right part were defined. The width of the central interest area was adjusted such as to cover the central wall that varied in extension, the size of the left and the right interest areas were identical. Fixations were assigned to the different interest areas. If not stated otherwise, the initial fixations directed towards the central interest area were removed, as these fixations resulted from the requirement to look at the fixation cross before stimulus onset.

In order to compare fixation patterns between stimuli, a 30×30 grid was imposed on the stimuli and fixations were assigned to the corresponding grid-cells. Fixation density was calculated separately for the horizontal and vertical image dimension by summing up the number of fixations along the vertical or horizontal grid dimension. Each entry of the resulting two vectors with 30 entries each were then divided by the sum of the entire vector (see Fig. 3). Only fixations before participants reported their response (Experiments 1 and 2) entered this analysis.

Results

Behavioral data

Participants displayed a small yet significant tendency to choose the right path option [$54.07 \pm 3.70\%$: t test against chance level (50%): $t(19) = 2.28, p = .03$]. Their tendency to produce stereotypical responses was analyzed for each route. We evaluated which path option was chosen more often and divided the number of choices for this option by the total number of responses for that route, resulting in values between .5 when participants chose both path

options equally often and 1 when they always chose the same path option. Note, that values are always larger than or equal to .5 and a value of exactly .5 is only possible for routes with an even number of responses. Chance level for this measure is .67, the participants' value was $.66 \pm 0.02$. In 54.78% of the responses within one route, they switched from the left to the right or vice versa [t test against chance level (50%): $t(19) = 1.30, p = .21$]. Together, these analyses suggest that participants were not using simple search strategies such as making right or left turns only.

In order to analyze which spatial features influenced participants' path choices, we calculated the 'difference in the length of the longest line of sight' between path alternatives as well as the 'difference in the number of vertical straight line segments in the depth profile' between path alternatives for each stimulus. The predictive power of these measures for decisions was then tested. As the two measures were correlated ($r = 0.43$), a step-wise linear regression for the mean decision score was calculated including both factors. Difference of line of sight significantly predicted mean decision scores, $\beta = 0.64, t(29) = 4.36, p < .001$ and explained a significant proportion of variance in mean decision scores, $R^2 = 0.41, F(1, 28) = 19.04, p < .001$. Difference of number of vertical straight line segments, in contrast, did not significantly contribute to this regression model, $\beta = -0.25, t(29) = -1.64, p > .1$. In a step-wise forward and backward regression, line of sight was included and number of vertical straight line segments was excluded (in both cases), suggesting that the number of vertical straight line segments (i.e., complexity) did not contribute to participants' decisions over an above the impact of line of sight. On average, participants

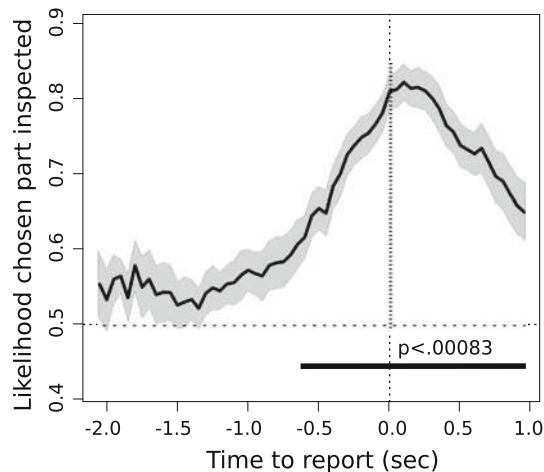


Fig. 4 The likelihood that the observer's gaze was directed towards the chosen part of the image (*left/right*) plotted against time (synchronized at time when decision was reported). The *black bar* indicates when the gaze bias was significantly different from chance level. The data represents the average across observers ($n = 20$) and trials ($n = 30$)

424 chose the path option featuring the longer line of sight in
425 60% of the cases.

426 Response times for the different stimuli ranged between
427 1,793 and 2654 ms (mean 2,277 ms). Marginally significant
428 correlations were observed between response times and
429 both, the total number of edges in the depth profiles
430 ($r = 0.35$, $p = .06$), and the rated complexity of the stimuli
431 ($r = 0.35$, $p = .06$)

432 Eye movement data

433 *Gaze shifts* After leaving the central interest area, partici-
434 pants on average made 6.20 fixations, crossing the mid-line
435 2.14 times, before reporting their decision. The first 6 fixa-
436 tions were characterized by an increase in eccentricity
437 ($r = 0.87$, $p = .02$) suggesting that participants scanned the
438 images from the center to the edges and inspected both
439 sides of the images before reporting their decision.

440 *Gaze bias* The likelihood that observer's gaze was
441 directed towards the eventually chosen part of the stimulus
442 changed over the time course of the trials (see Fig. 4, left).
443 Approximately 700 ms before participants reported their
444 decisions, the likelihood of inspecting the chosen path
445 option significantly increased above chance level, reaching
446 a maximum of 82.18% around the time when decision was
447 reported. Statistical significance was assessed by *t* test com-
448 parisons of gaze bias against chance level (50%) for each of
449 60 time points (50 ms intervals from 2 s before the response
450 until 1 s after the response). In order to correct for multiple
451 comparisons, alpha level was set at $p < 0.00083$ (Bonferroni
452 adjustment).

Fixation patterns What parts of the scene did participants 453
inspect while making their decisions? The right part of 454
Fig. 5 summarizes fixation patterns for the horizontal and 455
vertical stimulus location separately. Most noticeably the 456
distribution of fixation density along the vertical image 457
position was sharply tuned just below the horizontal center 458
line of the images and there was very little variance in the 459
fixation positions along the vertical position between stimuli. 460
Accordingly, the average correlation between fixation 461
densities along the vertical image dimension recorded for 462
the 30 stimuli was very high ($r = 0.97$). The distribution of 463
fixation density along the horizontal image position, in con- 464
trast, was rather broad and there were considerable differ- 465
ences between the stimuli (Fig. 5, right). Differences in 466
fixation patterns between the different scenes were primar- 467
ily due to differences in the horizontal dimension. Further 468
analysis will therefore focus on the horizontal axis. 469

The averaged fixation density along the horizontal image 470
location revealed two maxima, left and right of the vertical 471
centerline of the images that relate to the two path options 472
that participants inspected and compared while deciding 473
between them (top right panel of Fig. 5). Figure 6 exempl- 474
arily displays the fixation densities along the horizontal 475
position for three single stimuli. A qualitative analysis of 476
fixation behavior for these stimuli suggests that participants 477
paid close attention to the parts of the image in which the 478
lines of sight were particularly long (left and middle exam- 479
ple in Fig. 6). Furthermore, fixation densities of the right 480
panel in Fig. 6, in which the longest lines of sight were 481
identical for both choice alternatives, suggests that fixation 482
density was also modulated by aspects of the local spatial 483
complexity. 484

Taking these qualitative observations into account, a 485
novel approach relating gaze behavior to geometrical prop- 486
erties of the depicted scenes is presented below. Predictions 487
for gaze behavior will be derived by analyzing purely geo- 488
metrical features of the scene depicted. 489

Discussion 490

Which path option do we explore when searching in unfa- 491
miliar environments? Participants showed a tendency to 492
choose the option with the longer line of sight. Accord- 493
ingly, a qualitative analysis of fixation patterns suggests 494
that they paid attention to areas in the environment that fea- 495
tured long lines of sight (see Fig. 6; quantitative analyses of 496
fixation patterns are reported below). This suggests that 497
participants' gaze behavior reflects the significance of long 498
lines of sight for their path choices. While related strategies 499
have been demonstrated in other navigation and route 500
selection studies (e.g., Golledge, 1995; Bailenson, Shum, & 501
Uttal, 2000; Conroy Dalton, 2003), it remains unclear why 502
participants chose the option with the longest line of sight. 503

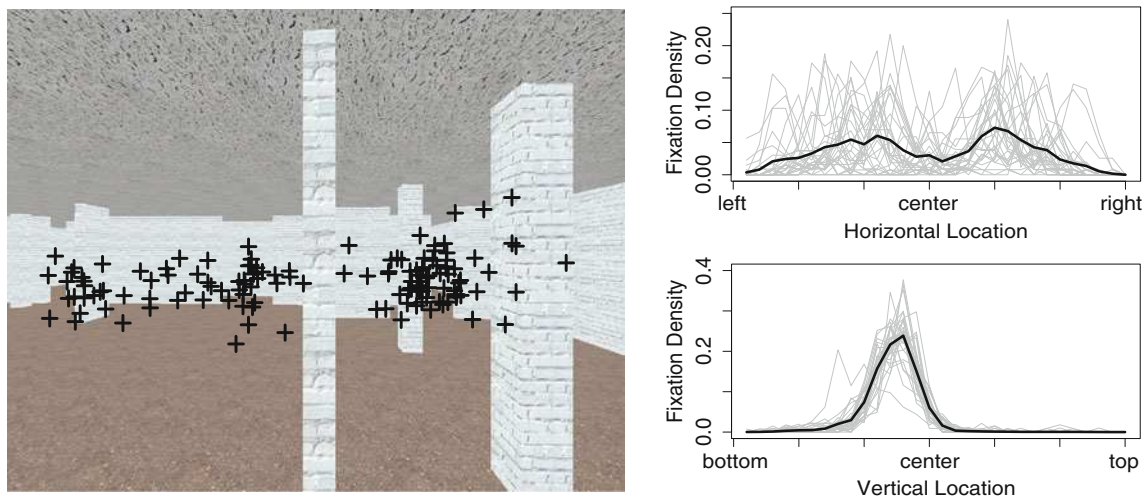


Fig. 5 *Left* Fixation pattern for one of the stimuli; *right* fixation densities for all stimuli for the horizontal (*top*) and vertical (*bottom*) image location. *Grey lines* depict fixation densities for the single stimuli (ar-

eas under curve sum up to 1); the *black lines* reflect the average over all 30 stimuli

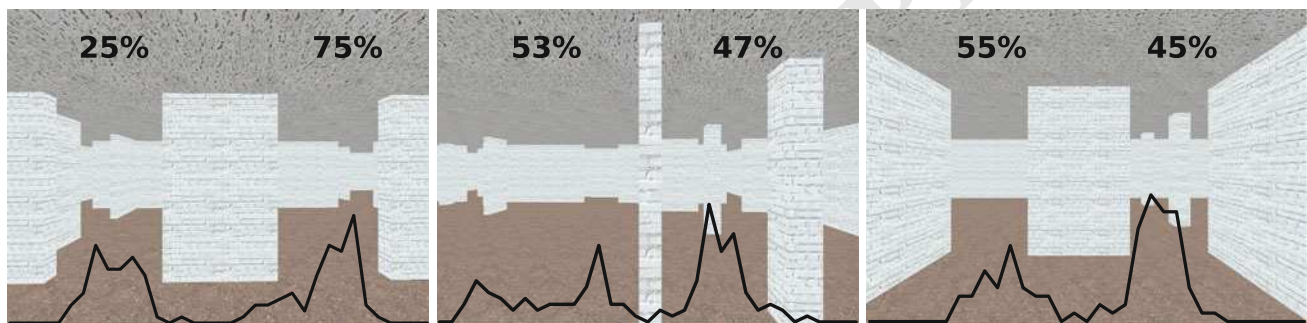


Fig. 6 Exemplary fixation densities plotted on top of three of the stimuli: Fixation densities (*black lines*) are plotted as a function of the horizontal position in the image. The *numbers* relate to the percentages the left or right path option was chosen

504 A possible explanation is that this path option promises
505 greater information gain when traveling along than the
506 alternative (Zetsche et al., 2009). However, further
507 research is needed to investigate this behavior.

508 The analysis of gaze behavior revealed a number of
509 interesting results. First, gaze behavior reflected the spatial
510 decision-making process: approximately 700 ms before
511 observers reported their decisions, the likelihood that they
512 inspected the eventually chosen path option significantly
513 increased above chance level. While this is in line with ear-
514 lier research on visual decision making (e.g., Shimojo et al.,
515 2003; Simion & Shimojo, 2007), the results for the first
516 time revealed a robust gaze bias effect while making way-
517 finding decisions. This demonstrates gaze bias effects when
518 comparing alternative options within a single stimulus,
519 rather than when comparing multiple separated stimuli and
520 therefore puts decision making and gaze bias in a more
521 realistic context. Moreover, the results suggest that gaze
522 bias effects in visual decision making are rather broad phe-
523 nomena that can be found in different tasks (cf. Glaholt &
524 Reingold, 2009).

Experiment 2

525 Experiment 1 revealed a reliable gaze bias in a spatial
526 search task in which participants were free to decide
527 between options. In that sense, the task was similar to other
528 visual decision-making tasks for which gaze bias effects
529 have been reported (Glaholt & Reingold, 2009). Wayfind-
530 ing, however, often requires the recognition of spatial situa-
531 tions encountered before and the encoding and decoding of
532 earlier decisions or movements. One prototypical example
533 is that of route navigation whereby the task is to memorize
534 and later retrieve movement decisions at choice points
535 (Trullier, Wiener, Berthoz, & Meyer, 1997). The aim of
536 Experiment 2 was to investigate gaze behaviour in a task
537 that was sought to resemble such route learning. Specific
538 interest concerned whether gaze bias effects can also be
539 observed in situations in which participants were instructed
540 about their choice rather than making them and when
541 recalling these earlier choices. Additionally, we were inter-
542 ested in the environmental features that participants
543 attended to during encoding and retrieval.
544

545	Methods	<i>Eye-movement data</i>	589
546	<i>Participants</i>	The analysis of the eye-movement data was identical to Experiment 1.	590 591
547	Twenty subjects (mean age 24.71 ± 2.87 years) participated in the experiment. They were mostly university students and were paid 8 Euros an hour.	Results	592
548			
549			
550	<i>Stimuli</i>	<i>Behavioral data</i>	593
551	The stimuli used in Experiment 2 were identical to those of Experiment 1.	Participants correctly recalled the required path option in 83.98% of the trials. An ANOVA did not reveal a main effect of the number of decisions to remember (ranging between 4 and 8) on memory performance [$F(4, 76.57) = 0.38, p = .83$].	594 595 596 597
552		Memory performance in the decoding phase could neither be predicted by measures of stimulus complexity [rated complexity ($r = -0.14, p = .45$), total number of straight line segments in the depth profiles ($r = -0.09, p = .63$), nor by the rated symmetry of the stimuli ($r = 0.23, p = .23$)].	598 599 600 601 602
553	<i>Procedure</i>	Response times were shorter in the encoding phase than in the decoding phase (1,960 vs. 2,199 ms t test $t(19) = -2.49, p = .02$). Response times during the decoding phase was different for correct and incorrect responses (correct: 2,116 ms; incorrect: 2,693 ms; t test $t(18) = 4.50, p < .001$, one participant was removed from this analysis as he/she provided correct answers only).	603 604 605 606 607 608 609
554	Participants first read a description of the experiment along with a set of instructions stating that their task was to follow and remember a predefined route. The experiment consisted of several routes, each of which was subdivided into an encoding phase and a decoding phase.	Eye movement data	610
555			
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558			
559	In the <i>encoding phase</i> , participants were presented with a series of images depicting choice points. Prior to the presentation of each stimulus, participants received a text message on the screen instructing them to either choose the left or right path option. They were told to inspect the stimulus and press the corresponding button (left/right cursor key) as soon as they were convinced that they would remember the depicted scene along with the required response. Before a novel stimulus was presented, participants fixated a small cross in the center of the screen and pressed the 'Space' bar.	<i>Gaze shifts</i>	611
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581	Analysis	The average number of gaze shifts between the three interest areas (left, middle, and right part of the image) was smaller in the encoding than in the decoding phase (1.96 vs. 2.60: t test $t(19) = -3.46, p < .01$). Furthermore, during decoding participants shifted gaze more often during incorrect than during correct trials (correct: 2.46; incorrect: 3.49, t test $t(19) = -3.45, p < .01$).	612 613 614 615 616 617 618
582	<i>Behavioral data</i>	After leaving the central interest area, participants made 5.44 fixations—crossing the mid-line 1.43 times in the encoding phase; and 6.26 fixations—crossing the mid-line 1.91 times in the decoding phase before reporting their decisions. The first 6 fixations after leaving the central interest area were characterized by an increase in eccentricity in both the encoding phase ($r = 0.82, p = .05$) and the decoding phase ($r = 0.89, p = .02$). As in Experiment 1, these results suggest that participants scanned the images from the center to the edges, inspecting both sides.	619 620 621 622 623 624 625 626 627 628 629
583			
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588			
		<i>Gaze bias</i>	630
		In both experimental phases, participants displayed a significant gaze bias towards the chosen path option	631 632

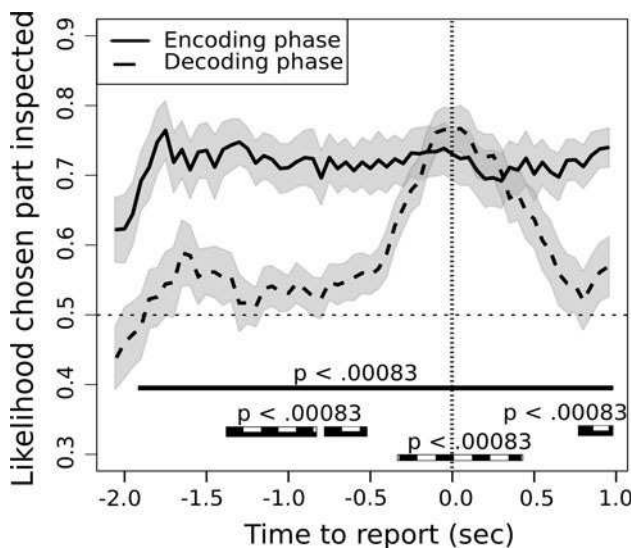


Fig. 7 The likelihood that the observer's gaze was directed towards the chosen part of the image (*left/right*) plotted against time (synchronized at time when decision was reported). The *solid black bar* and the *dashed black bar* indicate when the gaze bias in the corresponding conditions was significantly different from chance level. The combined *dashed/solid bar* indicates when the gaze bias effects differed significantly between the encoding and the decoding phase. The data represent the average across observers ($n = 20$) and trials ($n = 30$)

(see Fig. 7). The temporal dynamics of this bias, however, was different: in the encoding phase a significant bias was observed after 1,900 ms, i.e. immediately after stimulus onset (average response time 1,947 ms). This bias remained stable over the entire trial, even after the response was made. In the decoding phase participants initially distributed their gaze evenly across the two alternative path options. A significant gaze bias was observed only 350 ms before the response, reaching its maximum around the time of response and decaying afterwards. A comparison between encoding and decoding phase revealed significant differences in gaze bias both before and after the response was reported (between 1,450 and 500 ms before, and 800 ms after the response was reported; see Fig. 7). Statistical significance was assessed by t test comparisons of gaze bias [between conditions or against chance level (50%)] for each of 60 time points (50 ms intervals from 2 s before the response until 1 s after the response). In order to correct for multiple comparisons, alpha was set at $p < .00083$ (Bonferroni adjustment).

In addition, we compared gaze bias effects between experiments (Experiment 1, Experiment 2 encoding, Experiment 2 decoding). An ANOVA revealed a significant main effect of experiment ($F(2, 57) = 11.83, p < .001$). Overall, the gaze bias effect was strongest in the encoding phase of Experiment 2 (average bias over the 3 s period: .72), followed by Experiment 1 (.65) and the decoding phase of

Experiment 2 (.59). Pairwise comparisons revealed significant differences between all experiments and conditions.

Fixation patterns

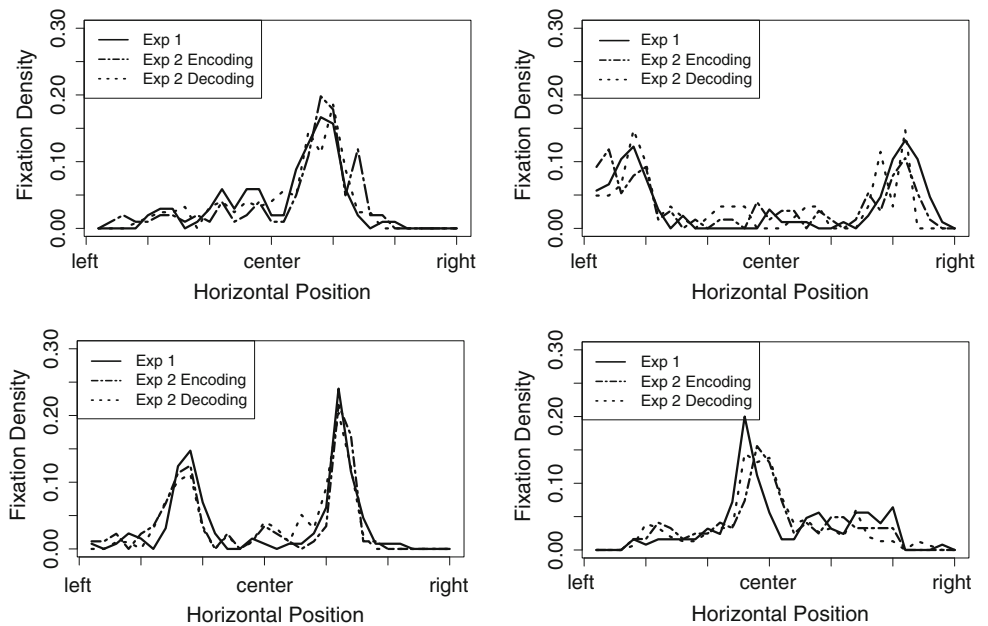
Fixation patterns in the encoding phase and decoding phase, as well as between Experiment 1 and Experiment 2 were strikingly similar. Figure 8 superimposes fixation densities along the horizontal dimension for four of the stimuli. The average correlation between the encoding and the decoding phase in Experiment 2 was $r = .92$ for the vertical position and $r = 0.81$ for the horizontal position. The average correlation between Experiment 1 and encoding phase of Experiment 2 was $r = 0.80$ (vertical) and $r = 0.78$ (horizontal). The average correlation between Experiment 1 and the decoding phase of Experiment 2 was $r = 0.86$ (vertical) and $r = 0.76$ (horizontal). These results demonstrate that, independent of the specific tasks and despite clear differences in the time course of gaze bias, visual attention was directed towards the same areas in the images.

Discussion

Performance in the route learning task was very good. Participants correctly recalled the required path choice in almost 84% of the cases. There was no significant effect of route length which was unexpected, as working memory load increases with more decision points to remember. A possible explanation is a floor effect—i.e. even with 8 decisions the memory task itself was fairly simple. While performance in the decoding phase could not be predicted by stimulus properties such as complexity (number of vertical straight line segments in depth profile or rated complexity) or symmetry, response times were correlated with memory performance. Response times in the decoding phase were shorter for correct trials and the number of gaze shifts in the decoding phase was significantly higher for incorrect trials. Most likely, these effects reflect participants' uncertainty in incorrect trials.

In addition to these performance-related effects, task-related influences on gaze behavior were observed. The gaze bias towards the chosen path option had a different temporal dynamic during encoding and decoding. Gaze bias effects did differ between all conditions in Experiments 1 and 2. For example, the gaze bias effect was stronger in Experiment 1 in which decisions were informed by evaluation of the path alternatives than in the decoding phase of Experiment 2 in which decisions were informed by memory retrieval. The temporal dynamic of the gaze bias effect also differed between the encoding and decoding phase of Experiment 2. During encoding, a significant bias was observed immediately after stimulus onset. During decoding, however, a

Fig. 8 Four examples of comparisons of fixation densities along the horizontal image location between Experiment 1 and the encoding phase and the decoding phase in Experiment 2



709 significant bias was observed only 350 ms before
 710 responding. In the context of wayfinding research, the
 711 early gaze bias during the encoding phase suggests that
 712 participants focused on the actual path when learning a
 713 guided route, rather than memorizing the entire scene
 714 and attaching directional information. The differences in
 715 gaze bias between encoding and decoding phase stand in
 716 contrast to earlier findings demonstrating similar scan-
 717 paths when encoding and later memorizing visual scenes
 718 (Humphrey & Underwood, 2008). The fact that partici-
 719 pants in this study were not engaged in solving spatial
 720 tasks, but merely memorizing images, suggests that the
 721 spatial nature of the tasks in current study did in fact
 722 result in specific influences on gaze behavior.

723 The analysis of fixation patterns revealed very consistent
 724 patterns between the encoding and the decoding phase in
 725 Experiment 2: the fixation densities along both, the hori-
 726 zontal and the vertical dimension were strongly cor-
 727 related. This is surprising at first glance, as task-related
 728 differences in the time course of the gaze bias have been
 729 observed (see above). It can, however, be explained by the
 730 fact that the left/right responses were balanced across stimu-
 731 pli: 50% of the participants had to choose the left path
 732 option of a particular stimulus, thus focusing primarily on
 733 that side during encoding; the remaining participants had to
 734 choose the other path option. Fixation patterns were also
 735 strongly correlated between Experiment 1 and Experiment
 736 2. While the task-related influences are evident primarily in
 737 the temporal characteristics of the gaze bias, the similarity
 738 in fixation patterns between experiments and conditions
 739 suggests that the image areas participants attended to most
 740 convey spatial information crucial to solving wayfinding
 741 decision tasks.

Experiment 3: free-viewing control

742

Motivation and procedure

743

744 Before analyzing in more detail which environmental fea-
 745 tures captured visual attention in Experiments 1 and 2, it is
 746 important to demonstrate that the recorded fixation patterns
 747 were, in fact, specific to the spatial tasks. To investigate this
 748 question a free-viewing control experiment was carried out.
 749 Sixteen participants were shown the same 30 stimuli used
 750 in Experiments 1 and 2 for 5 s each and their eye move-
 751 ments were recorded. Participants were not given a specific
 752 task other than inspecting the pictures they were shown
 753 (free-viewing task). Eye-movement data were analyzed as
 754 described in Experiment 1 (see Fig. 3), and fixation densi-
 755 ties along the horizontal dimension were compared to
 756 Experiments 1 and 2. In a structured but open-ended inter-
 757 view after the experiment, participants were asked what
 758 they were thinking when inspecting the stimuli. While such
 759 subjective reports are sometimes considered unreliable,
 760 recent work demonstrates that individual fMRI time series
 761 and eye-tracking data recorded during wayfinding experi-
 762 ments closely matched events from retrospective verbal
 763 reports (Spiers & Maguire, 2006, 2007). This suggests that
 764 in the context of wayfinding, verbal reports can provide
 765 important and reliable information about the tasks that par-
 766 ticipants are engaged in.

Results and discussion

767

768 As in Experiments 1 and 2 fixations were sharply tuned
 769 along the vertical dimension to an area just below the hori-
 770 zon, but varied considerably along the horizontal image

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- 771 location. Average correlations for fixation densities along
 772 the horizontal dimension for the 30 stimuli between the
 773 control experiment and Experiments 1 and 2 were $r = 0.74$
 774 demonstrating that the image areas inspected in this free-
 775 viewing condition were again similar to those in Experi-
 776 ments 1 and 2. As participants were not instructed to solve
 777 wayfinding decision-making tasks this suggests that the
 778 fixation patterns recorded in Experiments 1 and 2 were not
 779 specific to the spatial tasks. An analysis of the interviews
 780 after the experiments, however, offers an alternative expla-
 781 nation: 11 out of the 16 participants reported that they felt
 782 as if being in a maze when inspecting the stimuli. More
 783 importantly, 14 participants explicitly reported that they
 784 looked for path options and thought about how to navigate
 785 if they were actually given the chance to move (for exam-
 786 ples of responses, see [Appendix](#)). In other words, 87.5% of
 787 the participants reported that they were spontaneously
 788 engaged in path choice tasks: they analyzed the spatial
 789 scene, inspected and compared the available path options.
 790 This is most likely due to the nature of the stimuli that
 791 afford a corresponding interpretation. Participants sponta-
 792 neously assign a purpose and implicit task to the stimulus
 793 materials. These additional interpretations can hardly be
 794 conceptualized as low-level data-driven attentional pro-
 795 cesses, but rather appear to reflect high-level cognitive
 796 strategies that purposefully guide eye movements.
- 797 **Experiment 4: free-viewing vertical control**
- 798 Motivation and procedure
- 799 In Experiment 3, we demonstrated high correlations
 800 between the fixation patterns of Experiments 1 and 2 in
 801 which participants solved spatial tasks and the free-viewing
 802 condition of Experiment 3. While participants' retrospec-
 803 tive reports suggest that they were engaged in spatial deci-
 804 sion making in Experiment 3 even without being instructed
 805 to do so, an alternative explanation is that fixation patterns
 806 of Experiments 1, 2, and 3 were primarily driven by low-
 807 level image features and were not specific to the spatial
 808 tasks at all. In order to distinguish between these explana-
 809 tions we rotated the images by 90° in Experiment 4. This
 810 manipulation makes it less likely that participants interpret
 811 the images as spatial situations and should thus prevent
 812 them from spontaneously engaging in wayfinding tasks. At
 813 the same time the basic image features are not influenced
 814 by the manipulation. If participants' gaze behaviour was
 815 primarily driven by low-level image features, we expect
 816 similar fixation patterns as in Experiments 1 and 2, rotated
 817 by 90° . If, however, the fixation patterns in Experiments 1
 818 and 2 were specific to the spatial tasks, we expect a clear
 819 reduction of correlation between fixation patterns of
 Experiments 1 and 2 and those in this control experiment. 820
 18 participants were shown the same 30 stimuli used in 821
 Experiments 1 and 2 for 5 s each and their eye movements 822
 were recorded. As in the first control experiment, partici- 823
 pants were not given a specific task other than inspecting 824
 the pictures they were shown (free-viewing task). For the 825
 analysis, eye-movement data was first rotated back by 90° 826
 and then analyzed as described in Experiment 1. 827
- Results and discussion 828
- Average correlations for fixation densities along the hori- 829
 zontal image dimension for the 30 stimuli between Experi- 830
 ment 4 and Experiments 1 and 2 were $r = 0.27$. This is a 831
 significant reduction as compared to the correlation 832
 between fixation patterns of Experiment 3 and Experiments 833
 1 and 2 and [$r = 0.74$ vs. $r = 0.27$; $Z = 2.48$; $p = .01$ (two- 834
 tailed)]. These results demonstrate that rotating the experi- 835
 mental stimuli by 90° influenced gaze behavior, irrespec- 836
 tive of the fact that the local image features were not 837
 manipulated, strongly suggesting that the fixation patterns 838
 of Experiments 1 and 2 do not solely result from low-level 839
 image features but were in fact specific to the spatial tasks 840
 that required analyzing the spatial scene depicted. 841
- Wayfinding decision making and gaze behavior** 842
- While the coarse spatial layout of a scene can be computed 843
 without the need for selective visual attention (e.g., Oliva & 844
 Torralba, 2001, 2006), it remains an open question upon 845
 which environmental features such computation may rely. 846
 Or, in the context of this research: which features of archi- 847
 tectural environments are being processed during space 848
 perception and wayfinding decision making? The stimuli 849
 used here are particularly suited to approach these ques- 850
 tions since they predominantly depict spatial—i.e. geomet- 851
 rical—information. Moreover, due to the image 852
 manipulation the saliency of image areas depicting more 853
 distant parts of the environments, including openings and 854
 further path options, was selectively reduced. Fixations 855
 towards these areas are therefore unlikely to result from 856
 stimulus properties such as saliency. Rather these areas 857
 were inspected because they convey information crucial for 858
 comprehending the spatial situation and deciding between 859
 path alternatives. If that was true it should be possible to 860
 predict the gaze behavior recorded in Experiments 1 and 2 861
 by analyzing purely geometrical properties of the scenes 862
 inspected. 863
 Image saliency (Saliency Toolbox: Walther & Koch, 864
 2006) did, in fact, correlate only weakly with fixation den- 865
 sity: similar to the analysis presented in Experiment 1, the 866
 saliencies for the horizontal and vertical dimension were 867

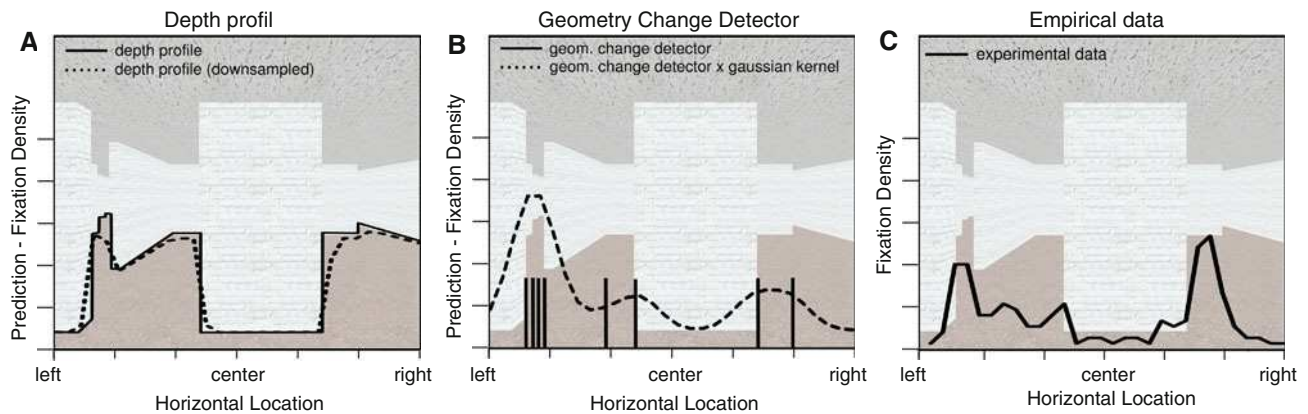


Fig. 9 Predictions for fixation densities of the two predictors (**a** Depth profile, **b** geometry change detector) for an exemplary stimulus and the corresponding empirical data (**c**)

868 calculated separately for each stimulus and were then corre- 905
 869 lated with the recorded fixation densities. The average corre- 906
 870 lation (after Fisher Z transformation) between the 907
 871 saliency and the horizontal fixation density was $r = -0.17$ 908
 872 and $r = 0.14$ for the vertical location, suggesting that 909
 873 saliency did not capture the image properties that guided 910
 874 visual attention in this particular setting. This, however, 911
 875 was not too surprising as saliency maps were designed for 912
 876 complex naturalistic scenes. Here, in contrast, we used 913
 877 screenshots of very simplistic VR sceneries that lack spe-
 878 cific objects. Furthermore, by manipulating the images, we
 879 removed some stimulus features that saliency maps are par-
 880 ticularly sensitive to, such as the high-contrast edges
 881 between walls and ceiling/floor.

882 What image areas did the participants inspect when mak- 914
 883 ing wayfinding decisions in the current setting? A qualita- 915
 884 tive analysis of gaze distributions suggests that participants 916
 885 were mostly attending to stimulus areas that allowed for 917
 886 long lines of sight (see Fig. 6). Given the wayfinding deci- 918
 887 sion-making task in the experiments this appears to be a 919
 888 sensible viewing strategy, simply because these areas 920
 889 depict the available path options. There is, however, 921
 890 another explanation: rather than merely processing image 922
 891 areas depicting more distant parts of the environment, 923
 892 observers attend to areas featuring changes in the local 924
 893 geometry as generated by occlusions, openings, and further 925
 894 path options. Architectural theory suggests that these struc- 926
 895 tural elements are of particular importance for wayfinding 927
 896 as they promise to reveal novel information about the envi- 928
 897 ronment (Peponis et al., 1997). In order to distinguish 929
 898 between these alternatives we developed quantitative mea- 930
 899 sures that extract the according information directly from 931
 900 the stimuli. The first measure—the depth profile—codes 932
 901 egocentric distance information from the beholder to the 933
 902 surrounding walls, thus directly capturing the length of the 934
 903 lines of sight in different image areas (Fig. 2). The second
 904 measure—the geometry change detector—identifies image

905 areas at which the local geometry of the depicted space 906
 907 changes, therefore highlighting areas with wall boundaries, 908
 909 openings and further path options. The predictive power of 910
 911 these two basic geometrical features for gaze behavior are 912
 913 investigated by correlating them to the gaze distributions 914
 915 measured in Experiments 1 and 2. We focus on fixation dis-
 916 tributions along the horizontal image dimension, as fixation
 917 probabilities along the vertical dimension hardly varied
 918 between stimuli (Fig. 5).

Depth profile 914

915 For each of the 30 stimuli the depth profiles were extracted 916
 917 (see “Methods” and Fig. 2). Information about which parts 918
 919 of the visual scene allow for long lines of sight is directly 919
 920 coded in the height or elevation of the depth profile. In 920
 921 order to derive predictions for participants’ gaze distribu- 921
 922 tion, the resolution of the depth profile was reduced from 922
 923 1,024 horizontal bins (the images were $1,024 \times 768$ pixel) 923
 924 to 30 horizontal bins by averaging the height of the depth
 925 profile over the respective bins (see Fig. 9a).

Geometry changes 924

925 Positions at which the geometry changes locally are cap- 926
 927 tured by orientation changes in the depth profile (see 927
 928 Fig. 9). Image areas featuring many geometry changes 928
 929 mark locations with high spatial information density.¹ Note 929
 930 that not the point at which the orientation changes itself but 930
 931 this point together with its context—i.e. the immediate sur- 931
 932 rounding—carries information about how the geometry 932
 933 changes. Hence, a Gaussian kernel (with a half-amplitude 933
 934 width of $\sigma = 1.6$ bins, relating to 2° visual angle) was applied 934
 935 to the individual geometry changes. This half-amplitude

¹ The 2D-detector described by Zetsche and Barth (1990) would high- 935
 936 light similar areas. 936

935 width was chosen as it roughly corresponds to the area of
936 foveal acuity thus capturing the local geometry that could
937 be perceived without further eye movements.²

938 As participants' fixation patterns were highly consistent
939 between Experiments 1 and 2, empirical data were pooled. The
940 average correlation over all 30 stimuli between the predictions
941 (depth profile, geometry changes) and the empirical data (cor-
942 relation coefficients were Fisher's Z transformed for averag-
943 ing) was $r=0.48$ for the depth profile and $r=0.64$ for the
944 geometry change detector. Given that earlier studies reported
945 strong central fixation biases independent of viewing task and
946 image features (e.g., Tatler, 2007), we added eccentricity as a
947 predictor. We then fitted a mixed effects model in R, using the
948 lmer function in the lme4 package (Bates, 2005), with the log
949 odds of fixation probability in each horizontal bin as dependent
950 variable, and with depth profile, geometry changes, and eccen-
951 tricity (squared distance from center) as fixed factors. Stimulus
952 was used as random factor. Removing random slopes was jus-
953 tified ($X^2(2) < 1$, ns.). All fixed factors were significant (all
954 $t_s > 10$). Not surprisingly, eccentricity turned out to be the
955 strongest predictor (cf. Tatler, 2007), followed by geometry
956 change and depth profile (eccentricity: estimate -0.006 , stan-
957 dard error $.0003$, $t = -20.38$; geometry change detector:
958 estimate = 13.37 , standard error = 0.72 , $t = 18.61$; depth pro-
959 file: estimate = 11.20 , standard error = 1.01 , $t = 11.15$).

960 Taken together, these results demonstrate that simple
961 analyses of geometrical features allow predicting fixation
962 patterns during space perception and wayfinding decision
963 making for the stimuli in this study. Together with results
964 from Experiment 4, this corroborates the notion that the
965 gaze behavior in Experiments 1 and 2 is the result of the
966 spatial nature of the wayfinding decision tasks and that it
967 relates to the analysis of the geometry and the comparison
968 of path alternatives. Moreover, the results suggest that par-
969 ticipants were attending image areas depicting changes in
970 the local geometry more than image areas allowing for long
971 lines of sight. These changes are not only related to plain
972 corners, but also to occlusions, openings, and further path
973 options which have to be inspected and compared when
974 making wayfinding decisions (cf. Peponis et al., 1997). Fur-
975 ther studies in our lab will address to what extent these
976 results generalize to wayfinding decision-making tasks that
977 are presented with richer and more complex naturalistic
978 scenes.

979 General discussion

980 The overall aim of this study was to investigate the relation
981 of gaze behavior and decision making in the context of

F3 ²Shape information can be perceived even parafoveally. Therefore the
F4 small amplitude width can be considered conservative.

982 wayfinding. In two experiments, participants were pre- 982
983 sented with images of choice points displaying two path 983
984 options and were either asked to decide between them in 984
985 order to search for an object that was hidden in the environ- 985
986 ment (Experiment 1), or they were instructed how to decide 986
987 at each decision point and were later asked to reproduce 987
988 these decisions (Experiment 2). While the first task sought 988
989 to resemble a search or exploration task in a novel environ- 989
990 ment, the latter task sought to resemble a route learning 990
991 task, in which a navigator is first led along a route and is 991
992 later asked to recall the path choices at different branching 992
993 points. Both experiments revealed reliable gaze bias effects 993
994 towards the chosen path option. In addition, the fixation 994
995 patterns were very similar between experiments, suggesting 995
996 that participants inspected the same environmental features 996
997 while choosing between path options. In two control exper- 997
998 iments we ensured that the fixation patterns recorded in 998
999 Experiments 1 and 2 were in fact driven by the spatial tasks 999
1000 and not by other low-level image features. 1000

1001 The gaze bias effects observed in Experiments 1 and 2 1001
1002 extend earlier results on visual decision making in non-spatial 1002
1003 domains (e.g., Shimojo et al., 2003) and demonstrate that 1003
1004 gaze behavior reflects spatial decision making also in the 1004
1005 context of wayfinding. While the experiments were not 1005
1006 designed to investigate whether gaze bias merely reflects 1006
1007 decisions or is also influencing them (cf. gaze-cascade 1007
1008 model, Shimojo et al., 2003), the results provide additional 1008
1009 evidence for the notion that gaze bias effects constitute a 1009
1010 rather general phenomenon of decision making that are 1010
1011 found in different tasks (Glaholt & Reingold, 2009). The 1011
1012 time course of the gaze bias effects in the experiments was 1012
1013 modulated by the task. For example, in the encoding phase 1013
1014 of Experiment 1, we observed a strong gaze bias directly 1014
1015 after stimulus onset that remained stable even after partici- 1015
1016 pants responded. In the decoding phase of Experiment 2, in 1016
1017 contrast, a significant gaze bias effect was observed much 1017
1018 later, only 350 ms before the participants responded. The 1018
1019 differences in gaze bias between conditions of Experiment 1019
1020 2 are interesting, as they are in contrast to recent work 1020
1021 reporting similar scan-paths between encoding and decod- 1021
1022 ing of natural scenes (Humphrey & Underwood, 2008; 1022
1023 Foulsham & Underwood, 2008). Participants in these stud- 1023
1024 ies, however, were not solving spatial tasks but were only 1024
1025 instructed to memorize the scenes. 1025

1026 The task-related modulation of the gaze bias strongly sug- 1026
1027 gests that the analysis of gaze behaviour can be a promising 1027
1028 means to reveal novel insights into the information process- 1028
1029 ing underlying specific wayfinding tasks. There is, for exam- 1029
1030 ple, a broad consensus that route knowledge can be 1030
1031 conceptualized as a sequence of stimulus-response pairs or 1031
1032 recognition-triggered responses (e.g., Trullier et al., 1997; 1032
1033 Kuipers, 2000; Mallot & Gillner, 2000). It is, however, an 1033
1034 open question which information exactly is memorized to 1034

1035 recognize the choice points along the route. As the current
 1036 virtual environments were lacking any objects that could
 1037 have served as landmarks, participants had to rely on geo-
 1038 metrical information. One possibility is that they memorized
 1039 the choice points by encoding the entire stimulus or spatial
 1040 situation (cf. snapshot-like memories, Cartwright & Collett,
 1041 1982; Gillner, Weiss, & Mallot, 2008); a second possibility is
 1042 that participants primarily focused on the path option belong-
 1043 ing to the actual route. In the encoding phase of Experiment 1
 1044 we observed a strong gaze bias towards the path option that
 1045 had to be chosen directly after stimulus onset. This suggests
 1046 that rather than memorizing the entire scene and attaching
 1047 directional information, participants memorized the visual
 1048 appearance of the actual path option they had to choose. This
 1049 encoding strategy does not require the explicit encoding of
 1050 directional information and is similar to a beacon strategy in
 1051 which the navigator moves towards a recognized landmark
 1052 (Waller & Lippa, 2007).


1053 Which information is depicted in the image areas that
 1054 captured visual attention in Experiments 1 and 2? Behav-
 1055 ioral results of Experiment 1 as well as qualitative analyses
 1056 of fixation patterns in both experiments suggested that local
 1057 geometric features, such as the line of sight and changes in
 1058 the geometry had an influence on what people did and
 1059 where they looked. We therefore analyzed the geometry of
 1060 the scenes and related it to participants' fixation patterns.
 1061 Inspired by isovist analysis (Benedikt, 1979), the visible
 1062 geometry of the scenes was described by depth profiles
 1063 from which also salient geometrical features were derived.
 1064 Specifically, the areas in the depth profile that correspond to
 1065 local geometry changes were detected. This geometry
 1066 change detector highlights structures such as corners, open-
 1067 ings, and occlusions and had a strong predictive power for
 1068 where people were looking when inspecting the two-
 1069 dimensional projections of three-dimensional complex
 1070 architectural indoor scenes. These results are in line with
 1071 architectural theory emphasizing the crucial role of these
 1072 structural elements for wayfinding (Peponis et al., 1997). In
 1073 real-world wayfinding, both geometric structure features
 1074 and object and landmark features interact to inform spatial
 1075 decision making. Recently, Frankenstein, Büchner, Ten-
 1076 brink, and Hölscher (2010) demonstrated the impact of
 1077 semantically rich landmarks alongside geometric informa-
 1078 tion. Current research in our labs addresses how well the
 1079 current results generalize to visual attention in more com-
 1080 plex natural scenes.

1081 It is noteworthy that results of Experiment 1 revealed
 1082 how the line of sight was a stronger predictor for partici-
 1083 pants' movement decisions than the number of vertical
 1084 straight lines in the depth profiles. For gaze behaviour,
 1085 however, changes in the local geometry (points between the
 1086 straight line segments in the depth profile) were a stronger
 1087 predictor than the depth profile itself (coding the length of

the line of sight). In other words, geometry changes are
 good predictors for fixation patterns, but weaker predictors
 for movement decisions, while line of sight is a good pre-
 predictor for decisions, but a weaker predictor for fixation pat-
 terns. Concentrating future research on this double
 dissociation could further inform our understanding of the
 intricate relation between gaze behaviour and decisions.

Which parts of the scene did participants attend to when
 inspecting the stimuli and while deciding between alterna-
 tive path options (Experiment 1) or while encoding or
 decoding path choices (Experiment 2)? For all stimuli, fixa-
 tions were narrowly tuned along the vertical axis, i.e. view-
 ers focused their attention around the horizon. This is a
 sensible viewing strategy in architectural indoor spaces in
 which the area around the horizon—as opposed to the floor
 and the ceiling—provides most information about the local
 geometry. Such a viewing strategy suggests that partici-
 pants were not merely responding to areas with high visual
 complexity or saliency, but were actually interpreting the
 three-dimensional structure of the sceneries depicted. This
 is further corroborated by a comparison of the saliency of
 the 30 stimuli with the actual fixation densities. Fixation
 densities along the horizontal axis systematically differed
 between stimuli, suggesting that participants directed their
 attention to specific areas in the environment. At the same
 time, participants' fixations patterns were similar between
 Experiment 1, 2 and 3. In other words, participants
 inspected the same areas, irrespective of the specific spatial
 task. A likely explanation for this is that these image areas
 are crucial for the comprehension and interpretation of the
 geometry of the depicted space. This is further corroborated
 by Experiment 4 in which participants viewed the same
 scenes but rotated by 90°. These images could not be as
 easily decoded as depicting spatial scenes and accordingly,
 fixation patterns did not closely match those of Experi-
 ments 1 and 2.

Taken together, the experiments in this paper show that
 gaze behavior is directed towards environmental features
 that have been suggested as decisive for spatial learning
 and decision making in navigation-related tasks. The atten-
 tional patterns are guided both by features of the environ-
 ment and by properties of the task at hand, be it route
 learning or spatial exploration. It is an important issue for
 spatial cognition research to untangle how environmental
 information, spatial abilities and cognitive strategies con-
 tribute to effective human navigation behavior. The paper
 underscores that spatial attention, measured via gaze behav-
 ior and fixation patterns, connects environmental features to
 spatial decision making. Overall, the results of this work
 suggest that the integrated analysis of navigation decision
 behavior and gaze behavior can play a key role in the inves-
 tigation of the information processing and the cognitive
 strategies underlying human wayfinding.

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1146 Appendix

1147 Control Experiment 1: structured interviews

1148 Excerpts of participants’ answers in the interviews after the
1149 control experiments are reported below. Specifically, the
1150 interviewer asked participants what they thought while
1151 inspecting the images in the control experiments. Here parts
1152 were selected that relate to the notion that participants
1153 spontaneously engaged in a wayfinding task.

1154 Participant 1: I noticed the possible routes and paths
1155 that could have been taken if I was in the environment.
1156 I focused on exploring these routes as this had more
1157 relevance and was of higher interest than the ceiling
1158 and walls.

1159 Participant 2: Where is the way out?

1160 Participant 3: Looked at it as a Labyrinth and thought
1161 about which way I would go/proceed to find my way. I
1162 was looking for ways out.

1163 Participant 4: I was looking for doors, exits. It
1164 reminded me of displays of museums, where you walk
1165 around. How would I walk around to look at the dis-
1166 plays that would be on the walls

1167 Participant 5: I looked for openings, like a clear path. It
1168 reminded me on playing computer games when I was
1169 growing up egoshooter. I was looking as if I was inside the
1170 room, it seemed like a maze, I was looking for a clear path

1171 Participant 6: It reminded me of a maze. I was looking
1172 for exits and entrances, sort of paths/ways to move on

1173 Participant 7: I mentally walked through the corridors,
1174 thought about how to go on

1175 Participant 8: First I attended to the center of the room,
1176 then I looked around

1177 Participant 9: It was some kind of maze—find your
1178 way—remember where I am—I tried to remember
1179 what was the configuration of walls. Ive looked what
1180 the configuration of walls looks like!

1181 Participant 10: I was looking how to go. It looked like
1182 you have to find your way in the labyrinth. I looked for
1183 ways to get around the obstacle in the middle! I ana-
1184 lyzed the pattern of this place, I imagined standing in
1185 the labyrinth and thought about how to move in it.
1186 Where is the fareset points in space?

1187 Participant 11: I was looking for spaces to walk down/
1188 it was like a maze, I realized there were two path
1189 options

Participant 12: I was looking for ways out. It reminded 1190
me of a maze, in a maze I look at everything , I looked 1191
for the layout. There were always two path choices in 1192
front and then more distant ones I inspected the distant 1193
path options, thinking about where I was gonna go. 1194

Participant 13: I felt like I was in a maze, it looked 1195
familiar. When I saw there was a gap in the wall I 1196
wanted to see what was here. There were walls and 1197
spaces and I wanted to see behind them. I could have 1198
gone in different places 1199


Participant 14: At first I was looking at the walls, then I 1200
thought if I was in that scene how would I escape I was 1201
looking for which way looked safest. There were differ- 1202
ences between right and left side. I was seeing it as if it 1203
was a maze, of which I was in the middle and deciding 1204
which way to go! 1205

Participant 15: (translated from German) I fixated the 1206
points that were furthest away—if somebody came 1207
around the corner here, I would detect that immedi- 1208
ately. When something was directly ahead of me, I 1209
looked at the wall and surveyed the surroundings . This 1210
looked like a maze, checked how somebody might 1211
come into the room, not how I could escape [semi- 1212
professional gamer, 300 days of gaming in 4 years]. 1213


Participant 16: I looked mainly at the entrances/exits, it 1214
felt like a maze , I was looking for my way out. 1215

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