

# Visual Search Behavior in Individuals With Retinitis Pigmentosa During Level Walking and Obstacle Crossing

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**PURPOSE.** Investigate the visual search strategy of individuals with retinitis pigmentosa (RP) when negotiating a floor-based obstacle compared with level walking, and compared with those with normal vision.

**METHODS.** Wearing a mobile eye tracker, individuals with RP and normal vision walked along a level walkway or walked along the walkway negotiating a floor-based obstacle. In the level walking condition, tape was placed on the floor to act as an object attracting visual attention. Analysis compared where individuals looked within the environment.

**RESULTS.** In the obstacle compared with level walking condition: (1) the RP group reduced the length of time and the number of times they looked *Ahead*, and increased the time and how often they looked at features on the ground (*Object* and *Down*,  $P < 0.05$ ); and (2) the visual normal group reduced the time (by 19%) they looked *Ahead* ( $P = 0.076$ ), and increased the time and how often they looked at the *Object* ( $P < 0.05$ ). Compared with the normal vision group, in both level walking and obstacle conditions, the RP group reduced the time looking *Ahead* and looked for longer and more often *Down* ( $P < 0.05$ ).

**CONCLUSIONS.** The RP group demonstrated a more active visual search pattern, looking at more areas on the ground in both level walking and obstacle crossing compared with visual normals. This gaze strategy was invariant across conditions. This is most likely due to the constricted visual field and inability to rely on inferior peripheral vision to acquire information from the floor within the environment when walking.

Keywords: visual impairment, visual field, retinitis pigmentosa, visual search, mobility

The ability to reorientate our gaze to look directly at objects when walking within our environment facilitates the acquisition of visual information from the fovea, the central part of the eye, which provides the highest level of visual acuity (VA). The information acquired from visually exploring the environment facilitates the planning of appropriate motor responses, allowing, for example, an individual to walk up to and safely step over a potential hazard, such as an obstacle on the floor. The eye movements that occur when executing a particular task provides the opportunity to understand more about the behavior of the individual during task execution. Indeed, the length and number of times an object or area within the environment is looked at provides an indication regarding the relevance to information processing (reflecting visual processing demands) and subsequent task execution.<sup>1</sup>

During walking gait, individuals with normal vision typically look several steps in advance,<sup>2-4</sup> and ahead at more distant areas in the environment.<sup>5,6</sup> This visual search behavior provides sufficient time to process the acquired visual information to execute sufficient motor responses to avoid any upcoming potential hazard (e.g., step over or walk around a floor-based hazard, c.f. Ref 7). During tasks that require the negotiation of a floor-based hazard, looking at the hazard occurs in the steps immediately prior to negotiation but not when stepping over.<sup>3</sup> When stepping over the hazard, visual

information acquired from the inferior part of the peripheral visual field (VF) is sufficient to modulate limb trajectory and ensure safe crossing.<sup>8,9</sup> While this strategy of relying on a combination of central and peripheral vision is sufficient in individuals with full (normal) vision to modulate walking gait when negotiating complex irregular terrain, individuals with peripheral VF loss would potentially be unable to acquire visual information in this manner and (presumably) be required to alter their visual search behavior accordingly.

To date, there is relatively little published research investigating the visual search behavior of individuals with peripheral VF loss when completing everyday mobility tasks. Previous research has shown that while walking a predetermined route and receiving a virtual view of the environment in a head-mounted display, individuals with retinitis pigmentosa (RP) predominantly looked down, whereas individuals with normal vision looked ahead.<sup>6</sup> On the other hand, Geruschat et al.<sup>10</sup> reported no difference in visual search behavior between individuals with glaucoma and normal vision when walking up to and crossing a street. Differences in findings between studies could be explained by the severity of VF loss in the respective visually impaired groups. Despite Geruschat et al.<sup>10</sup> reporting individuals with glaucoma having significantly smaller VF extent compared with their fully sighted participants (95° vs. 133°, glaucoma and visual normal, respectively), VF loss was



less severe in the glaucoma group compared with the RP group in the study by Turano et al.,<sup>6</sup> which ranged from  $9^\circ \times 8^\circ$  to  $30^\circ \times 28^\circ$ . It is likely that the more constricted VF in the RP compared with glaucoma group contributed to differences in findings between studies. Indeed, a more constricted VF would likely remove the ability to acquire visual information from the periphery to guide locomotion.

During level walking, while the length individuals with RP look at features within the environment has been explored,<sup>6</sup> to date the number of times an individual looks at key environmental features has not been investigated; previous research has also not compared visual search behavior between RP and normal vision during obstacle negotiation. When analyzing visual search behavior, both the length and number of times an area within the environment is looked at should be considered together. It is possible to increase the length of time looking at a particular area, but not increase how often it is looked at (i.e., one long fixation). Alternatively, looking at the same area for a short time period but a high number of times would result in a comparable total length of time as the previous example, but demonstrate very different visual search behaviors. It is necessary to distinguish between these two different visual search behaviors as an increased number of fixations has been linked to a reduction in efficiency of gaze behavior (c.f. Ref. 11).

In everyday life, we are required to negotiate a variety of terrain. For example, in some situations we are required to step over a floor-based obstacle, and on other occasions irregularities on the floor can simply be walked on and do not require a change in walking gait (e.g., stepping on a piece of litter on the floor). It currently remains unknown whether visual search behavior among those with peripheral VF loss changes as a function of terrain complexity, which presents an increased risk of falling (i.e., when negotiating an obstacle compared with walking across level terrain that is not uniform in its visual environment).

The current study had the two following aims: (1) determine whether individuals with RP and normal vision adopt a different visual search behavior during level walking (which is not uniform in its visual environment) compared with an irregular terrain that requires negotiation of a floor based obstacle; and (2) during level walking or obstacle negotiation, when compared with those with normal vision, determine whether individuals with RP differ in terms of the length and number of times they look at key features in the environment.

## METHODS

### Participants

The current study recruited individuals with RP. Retinitis pigmentosa is a genetic retinal dystrophy that primarily impairs peripheral vision.<sup>12</sup> Loss of peripheral vision among individuals with RP results in particular difficulty with mobility.<sup>13-20</sup> Participants with RP were recruited by advertising the study through the Retinitis Pigmentosa Fighting Blindness (RPFb) website, newsletter, social media pages, and through presence at the annual RPFb conference. A total of 17 individuals with RP were recruited to the study.

Successfully collecting data on eye movements using a mobile eye tracker with visually impaired individuals is difficult. This is because analysis of mobile eye tracking data predominantly uses electro-oculography, reflection-, or video-based methods for measuring eye movements. These approaches are dependent upon, during the calibration of the eye tracker, the individual's ability to look (using the fovea) at

visual targets at known locations. Visually impaired individuals with poor VA experience difficulties undertaking the calibration process, resulting in being unable to collect meaningful data. As a result, from the 17 individuals with RP recruited to the present study, 11 participants were not able to pass the initial calibration test when using the eye tracker. Of the 11 participants who did not pass the calibration, six were unable to see key features in the environment needed to confirm the calibration (due to their poor VA), four wore glasses (this makes a stable calibration difficult to achieve), and one had a drooping eye lid, resulting in being unable to ascertain a corneal reflection required for tracking. This resulted in six individuals with RP being retained for the study, a similar sample size to previous related studies, which presumably had the same difficulties.<sup>6,10,21,22</sup>

From the six individuals with RP on whom data collection was possible, one individual habitually used a mobility cane. To ensure homogeneity in the RP group, only individuals who did not habitually use a mobility aid (i.e., mobility cane or guide dog) when walking were included in this group ( $n = 5$ ). Data for the one cane user is presented separately from the RP group and can be found within the Appendix (A1). Five individuals with normal vision were also recruited who appropriately matched each individual within the RP group. The RP and visual normal group were matched in terms of age, weight, and height.

Health and physical fitness of all participants was assessed through a self-report questionnaire. Participants were excluded if they reported any history of neurologic or musculoskeletal disorders that could affect balance or gait, or had insulin-dependent diabetes, a history of eye disorders, or ocular pathology (except those that resulted in VF loss in the visually impaired group). The tenants of the Declaration of Helsinki were observed and Anglia Ruskin University's Ethical Committee approved the study. Written consent was obtained from each participant prior to participation.

### Visual Assessments

All visual assessments were completed using the participant's presenting vision for walking. Because both eyes are normally used to acquire visual information during gait, all visual assessments were completed binocularly. Visual acuity was measured using an Early Treatment Diabetic Retinopathy Study LogMAR chart at a working distance of 4 m, using a letter-by-letter scoring system (0.02 LogMAR). At 4 m, if participants were unable to read the largest letters on the LogMAR chart, shorter distances were used and the score adjusted accordingly. Contrast sensitivity (CS) was measured using the Pelli-Robson chart at 1 m and scored using the triplet method, with threshold considered as the final triplet at which the individual reads at least two of three letters correctly.<sup>23</sup> Visual field assessment was conducted binocularly using a Humphrey Field Analyzer (Carl Zeiss Meditec, Inc., Dublin, CA, USA) using the Standard  $45^\circ$  kinetic testing option. Extent of VF was determined by calculating where the isopter crossed the main axes on the VF plot to the nearest  $5^\circ$ . The four values were then averaged to provide a gross measure of the diameter of VF extent (in degrees).

### Recording of Eye Movements

Eye movements were recorded using an SMI iView ETG head mounted mobile eye tracker (version 1.0; SensoMotoric Instruments, Teltow, Germany) at 30 Hz. The eye tracker contains three cameras built into the glasses, an infrared camera to record movements of each eye and a high-definition camera (24 Hz) to record the visual scene. The eye tracker also

contains an integrated microphone to record audio. In order for the eye tracker to be calibrated, a three-point eye calibration was required to verify point-of-gaze; participants were required to look at key features in the environment (predetermined by the research team) and verbally indicate when a particular feature was being attended. The calibration was checked following every third trial. The spatial resolution of the system was  $0.1^\circ$ , with gaze position accuracy of  $\pm 0.5^\circ$ . Data from the eye tracker were recorded on a mini laptop (Lenovo X220; ThinkPad, Boston, MA, USA) with SMI iView ETG recording software installed (version 2.0; SensoMotoric Instruments). During testing, the eye tracker was connected to the laptop via a 2.5 m cable. The laptop was carried by a researcher who followed behind the participant (at a distance of  $\sim 2$  m). To ensure that the researcher could consistently remain at the correct distance behind the participant during the collection of data, participants were given a brief initial familiarization period, whereby they walked around the lab (not along the walkway or negotiating any obstacles) wearing the eye tracker. This allowed the researcher to learn the participant's typical walking speed. Using a researcher to carry the laptop was deemed more appropriate compared with asking participants to carry the laptop in a backpack because some participants may have been unaccustomed to carrying the added mass on their back and this may have disrupted their normal walking gait.

### Experimental Setup

Participants were required to walk along a walkway 12 m in length and 1.6 m wide. A curb made of 3 cm high and 1.8 cm wide timber (replicating the height of a low curb) was positioned along the edges (width) of the walkway. The walkway was set approximately in the middle of a research laboratory measuring 30 m in length, 9 m wide, and 7 m high.

**Level Walking Condition.** Participants were asked to walk along the walkway described above. Tape (60 cm long and 4 cm wide) similar in color to the brown medium density fiberboard (MDF) obstacle used in the obstacle crossing condition (see below), was positioned on the ground, to create a walkway, which was not uniform in its visual environment. The tape provided a salient feature within the travel path, which served to attract attention and also require the individual to determine whether it was part of a level walkway or presented an irregular terrain, requiring negotiation of an obstacle (see below). Not providing any salient feature on the walkway in the level walking condition would allow individuals to quickly identify between the two experimental conditions. The tape was positioned randomly between 5.95 and 6.05 m from the start position and removed during obstacle crossing trials.

**Obstacle Crossing Condition.** Participants were required to negotiate one of two different sized floor-based obstacles positioned along the walkway. An obstacle, either (3 or 10 cm in height, pseudorandomly chosen) was randomly positioned between 5.95 and 6.05 m from the start position. The obstacles (reflecting typical heights encountered in everyday life<sup>9,24</sup>) were constructed from MDF 1.8 cm thick and 62 cm long. The obstacles were light brown in color and presented a high contrast target on the background of the light gray laboratory flooring, thereby increasing the ease of identifying the obstacle and subsequently reducing the risk of tripping.<sup>25</sup>

The variation of  $\pm 10$  cm in object location (tape or obstacle) was to ensure that individuals did not become habituated with identifying and negotiating the object positioned at the same distance from their start position.

Electronic light gates (SmartSpeed; Fusion Sport, Summer Park QLD, Australia) were positioned at the start and end of the walkway. As the participant walked past the light gates, a single

'beep' was emitted. The auditory tone recorded by the eye tracker provided the start and end points to begin tracking the visual search data (and measure subsequent trial length).

Prior to data collection, participants were instructed that for each trial, they were required to walk along a predefined walking path where there may or may not be an obstacle present. No prior information was included specifying the number of objects that would be placed in the travel path, or the type of terrain they would walk along. Information provided to the participant pertaining to the specific task was deliberately vague to ensure that in each trial, participants actively searched the environment. Prior to the start of each trial, participants were not aware of the specific condition and were required to initially face the opposite way from the intended walking direction. This particular start position ensured that participants did not receive advanced visual information from the environment prior to the start of the trial. Participants were instructed that upon hearing the 'go' command, they were to turn around and walk along the walkway, and try not to trip over any object that may be in their travel path. Participants were instructed that they were not allowed to walk around the object. Once participants had walked to the end of the walkway, they were required to continue walking in a 'loop', and return to the initial start position. Of note, we were not interested in analyzing visual search behavior after completing the walkway and because of this, participants were free to walk anywhere in the laboratory to return back to the start position. While the researcher (carrying the laptop) remained silent as the participants navigated the walkway, when walking back to the start position, they engaged the participant in conversation. Level walking and obstacle crossing trials (both 3- and 10-cm height obstacles) were all completed three times, resulting in nine trials for each participant. All trials were presented in a pseudorandom order.

### Data Analysis

Point of gaze data from the eye tracker was analyzed offline using SMI BeGaze software (version 3.4; SensoMotoric Instruments) and was subject to frame-by-frame analysis. Each trial was tracked from the first frame the auditory noise from the light gates (denoting the start of the trial) was registered on the eye tracker's microphone up until the second auditory noise from the light gates was registered (denoting the trial being complete).

A similar categorization scheme was adopted to that presented by Turano et al.<sup>6</sup> In the current study, the same categorization scheme was used for level walking and obstacle crossing tasks (Fig. 1): (1) *Object*—looking directly at the obstacle or tape; (2) *Ahead*—looking at the wall straight ahead, the area between the wall and end of the walkway and looking in advance of the object within the walkway (up until the point of crossing the object); (3) *Down*—looking at the ground within the walkway prior to the object and at the ground within the walkway following crossing the object. Note that after crossing the object, the walkway area in advance of the object changes from being categorized as *Ahead* to *Down*; (4) *Floor*—looking on the ground, outside of the walkway; and (5) *Other*—looking at task irrelevant areas (areas not included in the aforementioned categories).

Each point-of-gaze in the real-time dynamic visual scene was mapped manually (frame-by-frame) to the categories identified above. To record the number of times participants looked from one place in the environment to another (i.e., number of gazes during the trial) a coding window was created to ensure that a clear saccade to look from one location to another was



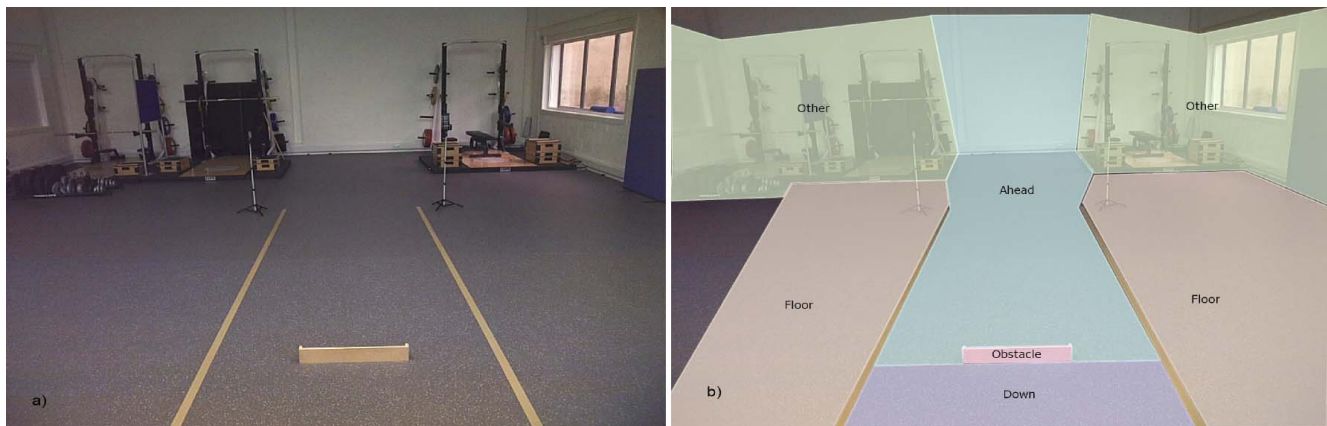


FIGURE 1. Illustration of environment when (a) negotiation obstacle (b) associated categories overlaid for tracking visual research.

categorized as a new gaze. The coding window accounted for looking to a new (different) area within the same area/category.

The following variables were used to analyze eye-tracking data:

1. Trial length (sec)—first frame the auditory noise from the light gates (denoting the start of the trial) was registered on the eye tracker's microphone up until the second auditory noise from the light gates was registered (denoting the trial being complete);
2. Scan rate (number/second [n/sec])—calculated by accounting for the total number of gazes within the trial divided by the total trial length;
3. Relative length of time looking within each category (percentage, %), *Ahead*, *Down*, *Object*, *Floor*, and *Other*; and
4. Relative number of times looking within each category (percentage, %), *Ahead*, *Down*, *Object*, *Floor*, and *Other*.

Differences in trial length will create bias/artificial inflation in the number or length of time spent looking within each category (i.e., see variables 3 and 4 above). Therefore, variables 3 and 4 were calculated relative to the total trial length and total number of gazes within the trial respectively.

### Statistical Analysis

All participants recorded a tracking ratio above 90%, deemed to be acceptable for analysis.<sup>26</sup> To assess the intrarater (same individual [MT] coded the same data twice) and interrater (two different researchers [MT, JB] coded the same set of data) reliability of the frame-by-frame analysis, 10% of collected trials were randomly chosen for duplicate analysis. Intrarater reliability agreement of 95% was found based upon the frame by frame mapping of the total number of gazes ( $r = 0.95$ ), the total number of times looking at the *Object* ( $r = 0.99$ ), the total time spent looking *Down* ( $r = 0.89$ ) and the total time spent looking *Ahead* ( $r = 0.99$ ). Interrater reliability agreement of 94% was found based upon the frame-by-frame mapping of the total number of gazes ( $r = 0.93$ ), the time spent looking at the *Object* ( $r = 0.97$ ), the total time spent looking *Down* ( $r = 0.92$ ), and the total time spent looking *Ahead* ( $r = 0.95$ ).

Conducting an initial analysis on all the dependent variables for obstacle and level walking trials highlighted that there was no significant effect of trial repetition ( $P > 0.05$ ). Thus, all data were averaged (separately) across level walking trials ( $n = 3$  trials) and obstacle-crossing trials ( $n = 6$  trials). Statistical analysis was limited to addressing specific questions relating to the study's aims: (1) comparison of visual search behavior within the RP group and visual normal group when completing

level walking compared with obstacle crossing trials; and (2) comparison of visual search behavior between those with RP and normal vision when completing level walking and obstacle crossing trials.

Statistical analysis was confined to RP and visual normal groups only. Descriptive information is only presented for the one RP-cane user (see Appendix A2). Level of significance was accepted at  $P < 0.05$ . Effect sizes were calculated using Cohen's  $d$ .

## RESULTS

### Descriptive Information

Pilot work confirmed that wearing the eye tracker ( $n = 4$  individuals with normal vision) did not significantly reduce total VF extent compared with not wearing the eye tracker ( $P > 0.05$ ,  $125 \pm 0^\circ$  habitual,  $113 \pm 5^\circ$  wearing the eye tracker). Individuals with RP who participated in the study ( $n = 5$ ) had VA of  $0.19 \pm 0.10$  LogMAR, CS  $1.56 \pm 0.23$  LogCS, and  $29 \pm 10$  years with visual impairment. Visual function in the individuals with RP who participated was better than those with RP who were not able to participate (due to issues with calibrating the eye tracker,  $n = 11$ ); VA  $0.66 \pm 0.40$  LogMAR and CS  $0.82 \pm 0.52$  LogCS. Of note, two individuals with RP who were not able to participate had no measurable VA or CS. The visual normal group had better visual function compared with the RP group retained for the study (Table 1).

There were no contacts with the *Object* during the obstacle-crossing task by any RP or visual normal participant (excluding RP-cane).

Visual field plots from the RP group and an exemplar from the visual normal group are shown in Figure 2.

### RP Group Level Walking Versus Obstacle Crossing

Trial length was significantly longer in the obstacle compared with walking task ( $8.83 \pm 0.42$  sec and  $8.47 \pm 0.51$  sec, respectively,  $P = 0.005$ ,  $d = 2.38$ ). Scan rate was significantly lower in the obstacle compared with walking task, with  $5 \pm 1$  n/sec and  $6 \pm 2$  n/sec in obstacle and walking tasks, respectively ( $P = 0.022$ ,  $d = 1.63$ ).

**Relative Time Looking at a Category.** Compared with the walking task, in the obstacle task the time spent looking *Ahead* was significantly reduced by 14%; walking  $36 \pm 18\%$ , obstacle  $22 \pm 16\%$ ,  $P = 0.001$ ,  $d = 3.60$ . While there was no significant difference in time looking *Down* (walking  $46 \pm 18\%$ , obstacle  $48 \pm 20\%$ ,  $P > 0.05$ ,  $d = -0.17$ ) there was a

TABLE 1. Participant Descriptive Information for Each Participant

	VA, LogMar	CS, LogCS	VF Extent, degree	Age, y	Height, cm	Weight, kg
RP_1	0.34	1.80	20	64	162	64
RP_2	0.10	1.50	85	27	178	76
RP_3	0.16	1.65	58	31	178	94
RP_4	0.24	1.20	8	73	174	80
RP_5	0.10	1.65	93	42	173	66
Norm_1	0.10	1.65	125	69	184	78
Norm_2	-0.08	1.65	120	28	177	65
Norm_3	-0.08	1.95	125	28	170	58
Norm_4	0.10	1.35	120	78	168	64
Norm_5	-0.12	1.95	125	44	167	61
RP	0.19 ± 0.10	1.56 ± 0.23	53 ± 38	47.4 ± 20.3	173 ± 7	76.0 ± 12.1
Norm	-0.02 ± 0.11	1.71 ± 0.25	123 ± 3	49.4 ± 23.2	173 ± 7	65.2 ± 7.7

VA, Visual acuity; CS, Contrast sensitivity; VF extent, visual field extent (average diameter).

significant increase in time looking at the *Object* in the obstacle ( $27 \pm 7\%$ ) compared with the walking ( $11 \pm 7\%$ ) task ( $P = 0.004$ ,  $d = -2.67$ ). There was no significant difference in time looking at *Other* (walking  $3 \pm 6\%$ , obstacle  $1 \pm 2\%$ ,  $P > 0.05$ ,  $d = 0.39$ ) or *Floor* (walking  $3 \pm 4\%$ , obstacle  $1 \pm 2\%$ ,  $P > 0.05$ ,  $d = 0.35$ ).

**Relative Number of Times Looking at a Category.**

Compared with the walking task, in the obstacle task the number of times looking *Ahead* was significantly reduced by 9%; walking  $47 \pm 13\%$ , obstacle  $38 \pm 15\%$ ,  $P = 0.007$ ,  $d = 2.30$ . This was accompanied by a significant increase in the number of times looking *Down* in the obstacle ( $39 \pm 15\%$ ) compared with the walking ( $33 \pm 11\%$ ,  $P < 0.05$ ,  $d = -1.23$ ) task and

significant increase looking at the *Object* in the obstacle ( $18 \pm 6\%$ ) compared with the walking ( $12 \pm 6\%$ ) task ( $P = 0.009$ ,  $d = -2.14$ ). There was no significant difference in the number of times looking at *Other* (obstacle  $2 \pm 3\%$ , walking  $3 \pm 4\%$ ,  $P > 0.05$ ,  $d = 0.26$ ) or *Floor* (obstacle  $3 \pm 4\%$ , walking  $5 \pm 5\%$ ,  $P > 0.05$ ,  $d = 0.35$ ).

**Normal Group Level Walking Versus Obstacle Crossing**

There was no significant effect of condition on trial length ( $7.90 \pm 1.08$  sec and  $8.22 \pm 1.31$  sec for walking and obstacle tasks, respectively,  $P > 0.05$ ,  $d = 0.86$ ). Scan rate was

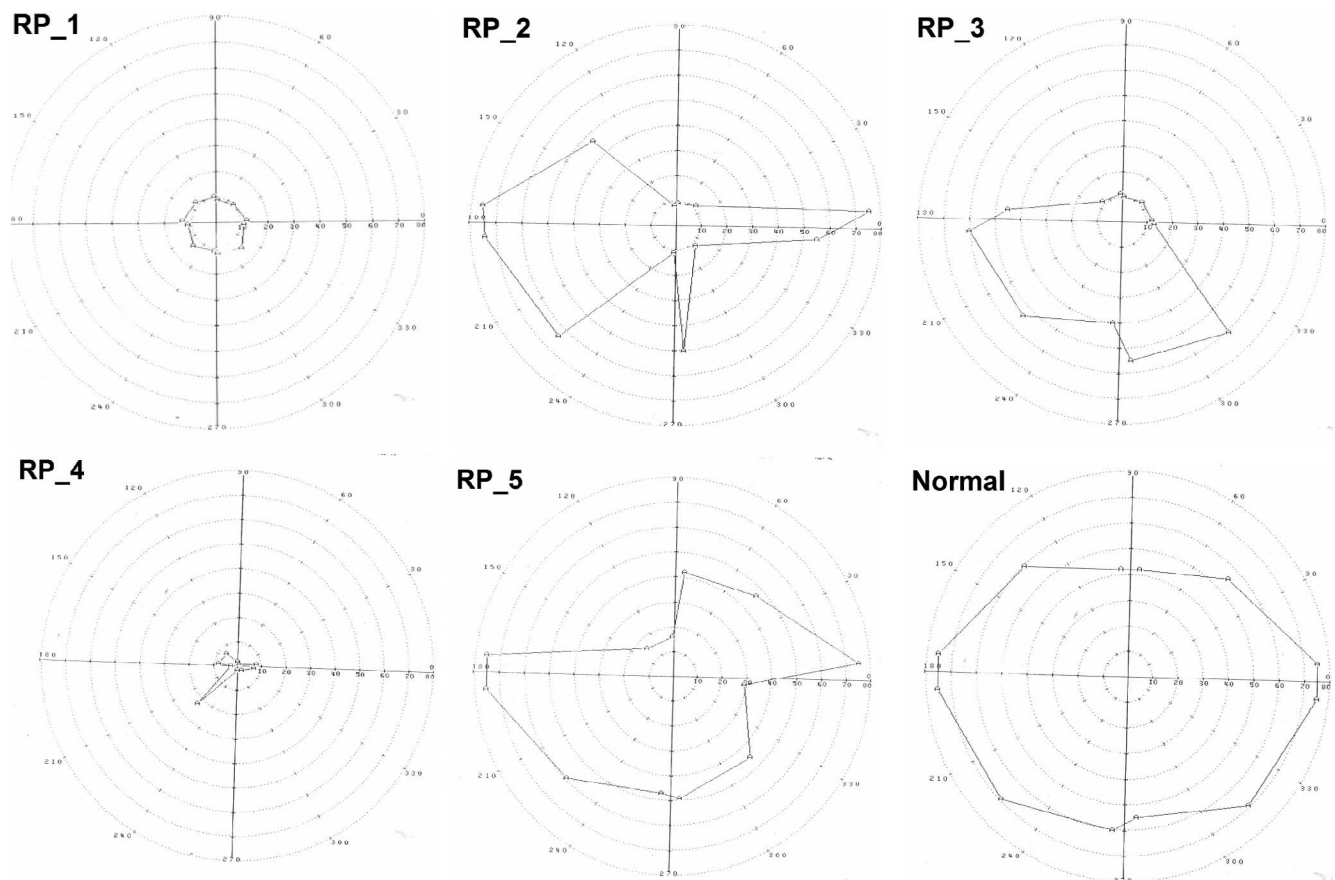


FIGURE 2. Visual field plots from RP group (RP\_1-5) and exemplar visual normal (normal).

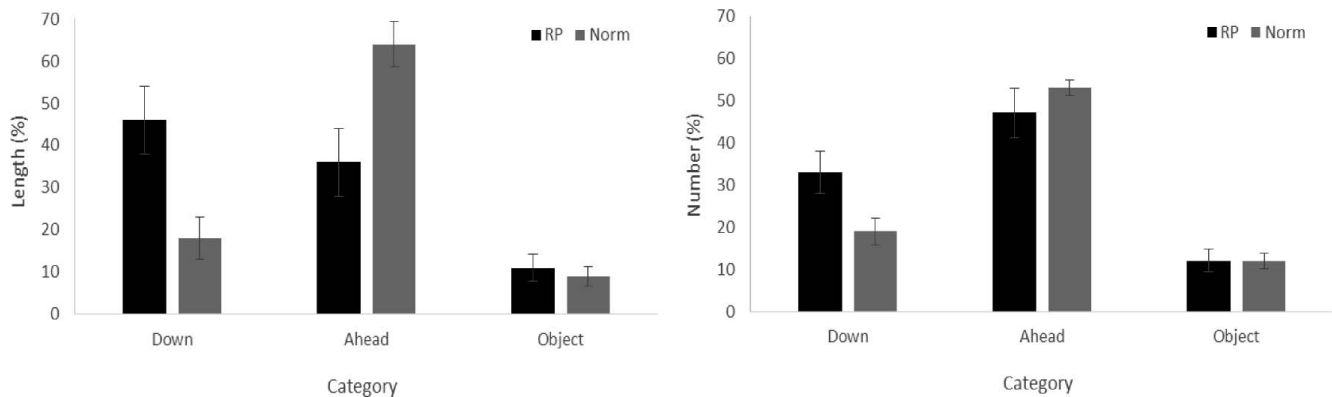


FIGURE 3. Length (a) and number (b) of times looking at categories *Down*, *Ahead*, and *Object* in the level walking condition for both RP and visual normal groups. Mean  $\pm$  SD.

significantly lower in the obstacle compared with walking task, with  $4 \pm 1$  n/sec and  $5 \pm 1$  n/sec in the obstacle and walking tasks, respectively ( $P = 0.014$ ,  $d = 1.87$ ).

**Relative Time Looking at a Category.** Compared with the walking task, in the obstacle task the time spent looking *Ahead* was reduced by 19% (walking  $64 \pm 12\%$ , obstacle  $45 \pm 24\%$ ), however this was not significant  $P = 0.076$ ,  $d = 1.06$ . While there was no significant difference in time looking *Down* (walking  $18 \pm 11\%$ , obstacle  $22 \pm 13\%$ ,  $P > 0.05$ ,  $d = -0.43$ ) there was a significant increase of 14%, in time looking at the *Object* in the obstacle ( $23 \pm 11\%$ ) compared with the walking ( $9 \pm 5\%$ ) task ( $P = 0.017$ ,  $d = -1.76$ ). There was no significant difference in time looking at *Other* (walking  $9 \pm 6\%$ , obstacle  $10 \pm 7\%$ ,  $P > 0.05$ ,  $d = -0.19$ ) or *Floor* (walking  $<1 \pm <1\%$ , obstacle  $1 \pm 1\%$ ,  $P > 0.05$ ,  $d = -0.60$ ).

**Relative Number of Times Looking at a Category.** There was no significant effect of looking *Ahead* in the walking compared with the obstacle task; walking  $53 \pm 4\%$ , obstacle  $48 \pm 10\%$ ,  $P > 0.05$ ,  $d = 0.64$ . There was no significant difference in the number of times looking *Down* in the obstacle ( $22 \pm 13\%$ ) compared with the walking task ( $19 \pm 7$ ,  $P < 0.05$ ,  $d = -0.44$ ). There was a significant increase in the number of times looking at the *Object* in the obstacle ( $15 \pm 4\%$ ) compared with the walking ( $12 \pm 4\%$ ) task ( $P = 0.014$ ,  $d = -1.86$ ). There was no significant difference in the number of times looking at *Other* (obstacle  $11 \pm 6\%$ , walking  $10 \pm 8\%$ ,  $P > 0.05$ ,  $d = -0.25$ ) or *Floor* (obstacle  $4 \pm 3\%$ , walking  $5 \pm 2\%$ ,  $P > 0.05$ ,  $d = 0.18$ ).

### RP Group Versus Visual Normal Level Walking

The RP group took  $8.47 \pm 0.51$  seconds and the visual normal group  $7.90 \pm 1.08$  seconds to complete the trial. There was no significant difference between groups ( $P > 0.05$ ,  $d = 0.68$ ). There was no significant difference in scan rate between groups,  $5 \pm 1$  n/sec and  $6 \pm 2$  n/sec in visual normal and RP group, respectively ( $P > 0.05$ ,  $d = 0.82$ ).

**Relative Time Looking at a Category.** Throughout the trial, the RP group spent on average 28% less time looking *Ahead* and 28% more time looking *Down* compared with the visual normal group. The RP group looked *Down* for  $46 \pm 18\%$  of the trial, compared with the visual normal group  $18 \pm 11\%$ , which was significantly different between groups ( $P = 0.017$ ,  $d = 1.85$ , Fig. 3a). The RP group looked *Ahead* for  $36 \pm 18\%$  of the trial, compared with the visual normal group  $64 \pm 12\%$ , which was significantly different between groups ( $P = 0.02$ ,  $d = -1.81$ , Fig. 3a). There was no significant difference between groups for *Object* ( $P > 0.05$ ,  $d = 0.40$ ), *Other* ( $P > 0.05$ ,  $d = -0.86$ ), or *Floor* ( $P > 0.05$ ,  $d = 0.79$ ). The *Object* was fixated 11

$\pm 7\%$  and  $9 \pm 5\%$  in RP and visual normal groups, respectively. *Other* was fixated  $3 \pm 6\%$  by the RP group and  $9 \pm 6\%$  in the visual normal group. *Floor* was fixated  $3 \pm 4\%$  and  $1 \pm 1\%$  in RP and normal groups, respectively.

**Relative Number of Times Looking at a Category.** The RP group looked *Down* 14% more often compared with the visual normal group. Of all gazes,  $33 \pm 11\%$  in the trial made by the RP group were *Down*, compared with  $19 \pm 7\%$  by the visual normal group. There was a significant difference between groups,  $P = 0.046$ ,  $d = 1.55$  (Fig. 3b). The number to times looking *Ahead* was not significantly different in the RP group compared with the visual normal group;  $47 \pm 13\%$  and  $53 \pm 4\%$  for RP and visual normal group, respectively ( $P > 0.05$ ,  $d = -0.68$ ). There was no significant difference between groups for *Object* ( $P > 0.05$ ,  $d = 0.08$ ), *Other* ( $P > 0.05$ ,  $d = -1.14$ ), or *Floor* ( $P > 0.05$ ,  $d = -0.03$ ). The *Object* was fixated  $12 \pm 6\%$  and  $12 \pm 4\%$  in RP and normal groups, respectively. *Other* was fixated  $3 \pm 4\%$  and  $10 \pm 8\%$  in RP and normal groups, respectively, and *Floor* was fixated  $5 \pm 5\%$  and  $5 \pm 2\%$  in RP and normal groups, respectively.

### RP Group Versus Visual Normal Obstacle Crossing

The RP group took  $8.83 \pm 0.42$  seconds and the visual normal group  $8.22 \pm 1.31$  seconds to complete the trial. There was no significant difference between groups ( $P > 0.05$ ,  $d = 0.59$ ). There was no significant difference in scan rate between groups,  $4 \pm 1$  n/sec and  $5 \pm 1$  n/sec in visual normal and RP groups, respectively ( $P > 0.05$ ,  $d = 1.32$ ).

**Relative Time Looking at a Category.** Throughout the trial, the RP group spent on average 23% less time looking *Ahead* and 26% more time looking *Down* compared with the visual normal group. The RP group looked *Down* for  $48 \pm 20\%$  of the trial, compared with the visual normal group  $22 \pm 13\%$  ( $P = 0.043$ ,  $d = 2.15$ , Fig. 4a). The RP group looked *Ahead* for  $22 \pm 16\%$  of the trial, compared with the visual normal group  $45 \pm 24\%$  ( $P = 0.11$ ,  $d = -1.61$ , Fig. 4a). The visual normal group looked at *Other* task irrelevant areas significantly longer compared with the RP group ( $P = 0.029$ ,  $d = -2.37$ , visual normal  $10 \pm 7\%$ , RP  $1 \pm 2\%$ ). There was no significant difference between groups for *Object* ( $P > 0.05$ ,  $d = 0.63$ ) or *Floor* ( $P > 0.05$ ,  $d = 0.40$ ). The *Object* was looked at  $27 \pm 7\%$  and  $23 \pm 11\%$  in RP and visual normal groups respectively. *Floor* was looked at  $1 \pm 2\%$  and  $1 \pm 1\%$  in RP and normal groups, respectively.

**Relative Number of Times Looking at a Category.** The RP group looked *Down* 17% more often compared with the visual normal group. Of all gazes,  $39 \pm 15\%$  in the trial made by the RP group were *Down*, compared with  $22 \pm 13\%$  by the



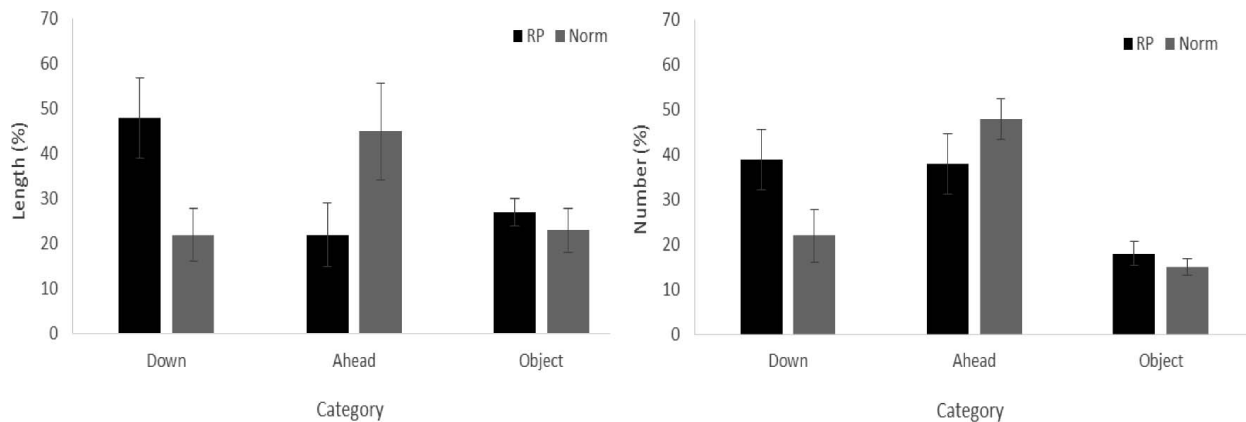


FIGURE 4. Length (a) and number (b) of times looking at categories *Down*, *Ahead*, and *Object* in the obstacle crossing condition for RP and visual normal groups. Mean  $\pm$  SE.

visual normal group ( $P=0.094$ ,  $d=1.70$ , Fig. 4b). The number of times looking *Ahead* was not significantly different in the RP group compared with the visual normal group;  $38 \pm 15\%$  and  $48 \pm 10\%$  for RP and visual normal groups, respectively ( $P > 0.05$ ,  $d=1.08$ ). The visual normal group looked at *Other* task irrelevant areas significantly more often compared with the RP group ( $P=0.011$ ,  $d=-2.93$ , visual normal  $11 \pm 6\%$ , RP  $2 \pm 3\%$ ). There was no significant difference between groups for *Object* ( $P > 0.05$ ,  $d=0.90$ ), or *Floor* ( $P > 0.05$ ,  $d=-0.51$ ). The *Object* was fixated  $18 \pm 6\%$  and  $15 \pm 4\%$  in RP and normal groups, respectively. *Floor* was fixated  $3 \pm 4\%$  and  $4 \pm 3\%$  in RP and normal groups, respectively.

**Correlations**

Correlation analysis only focused on the association between visual function and the categories *Ahead*, *Down*, and *Object*; deemed most important to this analysis. Data were collapsed across all participants and conditions. Results (Table 2) indicate that VA and CS did not correlate strongly with any dependent variables. While VF was not significantly associated with the analyzed variables, results demonstrate a clear trend with large effect sizes ( $r > 0.5$ ) for *Down* length  $-0.582$ ,  $P=0.078$  (Fig. 5a), *Ahead* length  $0.600$ ,  $P=0.067$  (Fig. 5b), and *Down* frequency  $-0.600$ ,  $P=0.067$ .

**DISCUSSION**

The visual information acquired from looking at key features within the environment facilitates safe navigation. To date, there is relatively little published research investigating the visual search behavior of individuals with peripheral VF loss when walking in the environment and when negotiating potential hazards. The current study investigated the visual search behavior of individuals with RP during a level walking task and when required to negotiate a floor-based obstacle. Visual search strategy among those with RP was also compared with individuals with normal vision when completing both tasks. Key findings from the study highlight that in both obstacle crossing and level walking tasks, the RP group demonstrated a visual search strategy different to those with normal vision, which remained invariant across conditions. Specifically, those with RP reduced the time looking *Ahead* to increase the time and how often they looked *Down* at the immediate locations on the walkway. The RP group did, however, view the *Object* in a comparable manner with the normal vision group in both level walking and obstacle-crossing tasks.

The *Object* was looked at in both tasks by RP and visual normal participants ( $27 \pm 7\%$  obstacle,  $11 \pm 7\%$  level walking for RP, and  $23 \pm 11\%$  obstacle,  $9 \pm 5\%$  level walking for visual normal). In both conditions, the *Object* was a salient feature within the travel path, which served to attract attention and allow participants to distinguish between the two objects; tape placed on the walkway or a floor based obstacle. Interestingly, there was no significant difference between groups (in length or how often) they looked at the *Object*. These findings demonstrate that the RP group were able to distinguish the key features of the *Object* in a comparable manner with the visual normal group. This is likely attributed to the relatively intact central vision among the RP group (Table 1).

While there was no significant differences in the length or number of occasions the *Object* was looked at between groups, changes in visual search behavior were observed (in both groups) during the obstacle compared with level walking task. In comparison with the level walking condition, when required to negotiate the obstacle both groups reduced the time looking *Ahead* (14% and 19% reduction in RP and visual normal, respectively) to increase the time (16% and 14% increase in RP and visual normal, respectively) looking at the *Object*. The increased time spent looking at the *Object* in the obstacle compared with level walking condition was required to precisely determine key features relating to object length, width, and fore-aft position, in an effort to minimize the risk of contact during the approach and subsequent crossing.<sup>8</sup>

In both obstacle and level walking conditions, the RP group spent approximately 50% of the entire trial looking *Down*

TABLE 2. Association Between VA, CS, and Entire VF Extent With Length and Frequency at *Ahead*, *Down*, and *Object* Categories

Category	VA		CS		VF (Entire)	
	r	P	r	P	r	P
Length						
<i>Ahead</i>	0.099	0.786	0.158	0.663	0.600	0.067
<i>Down</i>	-0.080	0.827	-0.166	0.647	-0.582	0.078
<i>Object</i>	0.024	0.947	-0.298	0.403	-0.436	0.208
Frequency						
<i>Ahead</i>	-0.045	0.901	-0.093	0.798	0.502	0.139
<i>Down</i>	-0.035	0.923	-0.168	0.643	-0.600	0.067
<i>Object</i>	-0.030	0.934	-0.029	0.936	-0.309	0.385

VA, visual acuity; CS, contrast sensitivity; VF extent, visual field extent (average diameter).

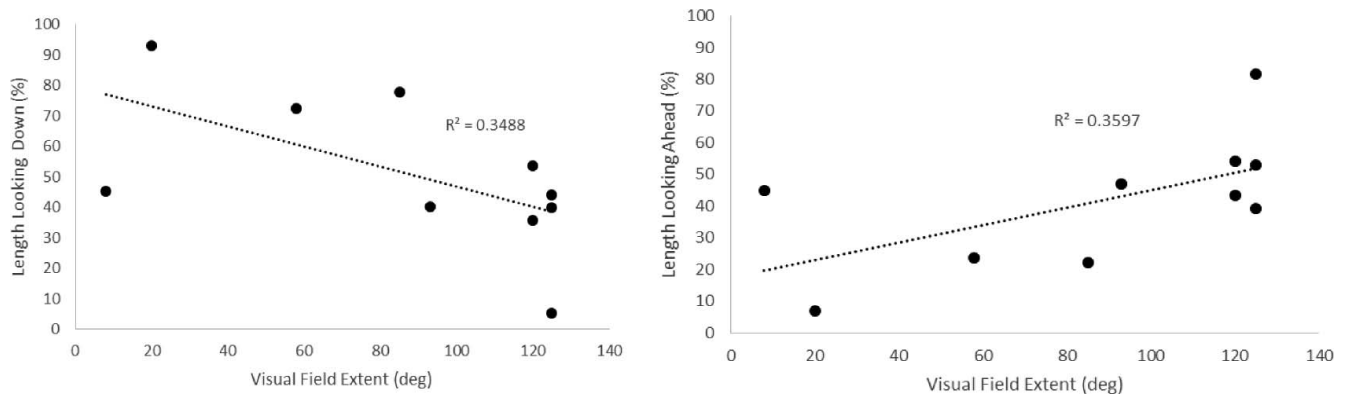


FIGURE 5. Visual field extent (degrees) associated with length looking (a) *Down* and (b) *Ahead*.

(Figs. 3a, 4a). This was approximately 30% more than the visual normal group (in both conditions). The increased time looking *Down* in the RP group was the result of reducing the time looking *Ahead* (28% reduction for level walking and 23% reduction for obstacle crossing compared with the visual normal group). These findings demonstrate that compared to those with normal vision, the downward areas in the visual scene, immediately in front are of increased importance to those with RP. This reorientation in visual search to look *Ahead* less and *Down* more confirms the findings published by Turano et al.<sup>6</sup> who suggested that this change in visual search behavior was a safety mechanism to ensure the RP participants' peripheral VF loss did not occlude any potential floor based hazard. We extend this previous work to demonstrate that the RP group also increased the number of times looking *Down* by 14% and 17% (level walking and obstacle crossing conditions, respectively) compared with visual normals. Through considering the number of times looking at a key area within the environment in combination with the length, these results suggest that the RP group were actively looking around the ground (presumably) to check for hazards, rather than adopting the same behavior as someone with normal vision; albeit looking at more immediate areas rather than looking several steps in advance<sup>2,3</sup> and ahead at more distant areas in the environment.<sup>5,6</sup> This active search pattern at the immediate areas of the travel path is most likely due to the constricted VF and inability to rely on peripheral vision to acquire information from the environment. This strategy adopted by the RP group would be advantageous in everyday life because we are frequently required to negotiate a multitude of floor-based obstacles. This safety strategy would increase the likelihood of someone with RP seeing a potential hazard on the floor, reducing their risk of tripping and falling. Further support for the suggestion that the RP group were actively looking around the ground to check for hazards as a result of their peripheral VF loss is provided from the results of the correlation analysis. Visual field extent was the key determinant associated with changes in visual search behavior (Table 2), demonstrating a large effect size for *Ahead* and *Down*, predicting 60% of the variance in length looking *Ahead* (Fig. 5b), 58% of the variance in length looking *Down* (Fig. 5a), and 60% of the variance in the number of times looking *Down*.

Individuals with RP self-report difficulties avoiding obstacles outdoors that appear in the superior peripheral VF (e.g., a low hanging branch from a tree).<sup>14</sup> This self-reported difficulty may be attributed to the reduced time the RP group spent looking *Ahead* (Figs. 3a, 4a). Compared with the visual normal group, the RP group looked *Ahead* for approximately 25% less time in both level walking and obstacle crossing tasks. The reduction in time looking *Ahead* in the RP group could also present a

problem when an unexpected change in the environment occurs. An unexpected change in the environment should produce a reorientation in attention.<sup>27,28</sup> In the RP group, with their constricted VF, if attention is currently focused on the ground, this reorientation in attention may either not occur, or occur too late to avoid accident. Predominantly looking *Down* could further be problematic for avoiding an oncoming pedestrian when walking down the street. Pedestrians use information based on the oncoming person's gaze to make judgments about the intended walking direction.<sup>29</sup> If an individual with RP is predominantly looking down, this may make it harder for the oncoming pedestrian to predict their future movements (c.f. Ref. 30).

While the current findings support and extend the work published by Turnao et al.,<sup>6</sup> they do not support the work published by Geruschat et al.<sup>10</sup> Geruschat et al.<sup>10</sup> reported no difference in visual search behavior between individuals with glaucoma and normal vision when walking up to and crossing a street. The glaucoma group recruited by Geruschat et al.<sup>10</sup> recorded an average binocular VF of 95°. In the current study, the RP group recorded a smaller average VF of  $53 \pm 38^\circ$  (range, 8°–93°); similar to the values reported by Turano et al.<sup>6</sup> Collectively, the work published by Geruschat et al.,<sup>10</sup> Turano et al.,<sup>6</sup> and the current study suggests that changes in visual search behavior among those with peripheral VF loss may only occur once VF loss reaches a certain point. Further research is required to better understand where this threshold may lie.

When completing both level walking and obstacle crossing trials, the normal vision participants often looked at *Other*; task irrelevant areas within the environment. Previous research has suggested that familiarity with a route increases the time spent looking at task irrelevant objects for the purpose of entertainment or distraction (e.g., looking at a picture on a wall when walking along a corridor).<sup>6</sup> None of the participants recruited in the current study were familiar with the environment. Therefore, the time spent looking at task irrelevant areas in both level walking and obstacle conditions indicates that concurrent visual information from the fovea was not necessary to safely negotiate these terrain among those with normal vision. Similar research has shown that among visual normals, concurrent visual information from the travel path is not required while engaging with a mobile phone and negotiating complex terrain<sup>31</sup> or when cycling on the road.<sup>32</sup> In the current study, the RP group spent little time looking at task irrelevant areas. This is likely a combination of requiring increased visual information from the environment to plan subsequent movement and/or detect hazards. Furthermore, compared with those with normal vision, everyday tasks place an increased mental effort upon those with severe visual impairment.<sup>33</sup> Because information processing capacity of the



working memory is limited within humans,<sup>34,35</sup> this likely results in little spare capacity within working memory to undertake additional tasks, such as looking at task irrelevant areas within the environment while walking.

### Limitations

In the current study, due to the impact moving the object would have on the analysis of visual search behavior, from trial to trial, it was necessary to position the object with relatively narrow variation on the walkway. Dramatically varying, between trials, the amount of time available to look down before crossing the object (through placing the object closer or further from the start position) would have added large variation into the data, masking any potential important findings. This would also apply to the amount of time available to look in advance of the object. It is possible that presenting the object (tape or obstacle) within a relatively narrow location along the travel path may have resulted in the participants learning its location. However, when analyzing visual search behavior at the tape and obstacle, when collapsed across groups, there was no significant difference between the first and last trial repeat for fixation length (tape—first and last repetition 11% and 10%, respectively; obstacle—first and last repetition 26% and 25%, respectively) and number of times looking at the object (tape—first and last repetition 12% for both; obstacle—first and last repetition 17% and 15%, respectively,  $P > 0.05$ ); there was no significant difference when separated for group ( $P > 0.05$ ). Furthermore, when analyzing whether participants became habituated to the experiment, investigating time to complete the trial (which provides an indication of task familiarity), when collapsed across groups, there was no significant difference ( $P > 0.05$ ) in trial length between the first and last trial repetitions (tape—first and last repetition  $8.26 \pm 1.00$  seconds and  $8.06 \pm 0.81$  seconds, respectively; obstacle—first and last repetition  $8.55 \pm 1.08$  seconds and  $8.51 \pm 1.02$  seconds, respectively); there was no significant difference when separated for group ( $P > 0.05$ ). We are therefore confident that the object placement did not impact visual search and subsequent walking behavior.

### CONCLUSIONS

The current study investigated the visual search strategy of individuals with RP during level walking and obstacle crossing, and when compared to those with normal vision. Findings from the study highlight that in both obstacle crossing and level walking tasks, the RP group demonstrated a visual search strategy different to those with normal vision, which remained invariant across conditions. Compared to participants with normal vision, those with RP looked *Ahead* less and instead looked for longer and more often *Down*. This active search pattern at the more immediate areas of the travel path is likely due to the constricted VF and inability to rely on peripheral vision to acquire information from the environment. The RP group did, however, view the *Object* in a comparable manner with the normal vision group in both level walking and obstacle crossing tasks. As there were no contacts with the *Object* during the obstacle-crossing task by any RP participant (excluding RP-cane), this suggests that for this particular task, the visual search strategy was effective to allow safe navigation of the environment.

Previous research has demonstrated that it is possible to train eye movements. Seiple et al.<sup>36</sup> trained individuals with AMD to make increasingly large eye movements in reading tasks and this resulted in improvements in reading speed. Ong et al.<sup>37</sup> and Kerkhoff et al.<sup>38</sup> trained individuals with

hemianopia to make more effective saccades in their blind regions, which increased visual search performance. Future research should therefore investigate whether it is possible to improve the visual search behavior of those with severe peripheral VF loss, in the attempt to increase their independence within the environment.

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## APPENDIX

A1. The RP-cane user was aged 73 years, had mass 72 kg, and height 173 cm. Visual acuity and CS were 1.3 LogMAR and 0.15 LogCS, respectively. Visual field entire extent was 13° diameter and he had 42 years with visual impairment.

A2. The RP-cane participant only completed one trial when completing the level walkway condition and two trials in the obstacle crossing condition (1 trial for each obstacle height). When negotiating the obstacle, in both instances the cane user walked into the object. Upon the second contact, it was deemed unsafe to continue data collection. Trial time was 16.23 seconds in the level walking and 17.78 ± 0.85 seconds in the obstacle crossing condition. With little difference between trial times, the remaining data is presented as an average across the both walking and obstacle conditions (Table A1). Average scan rate was 4 ± 3 n/sec.

**TABLE A1.** Retinitis Pigmentosa Cane User Visual Search Data for Each Category

	Length, %	Number, %
Floor	56 ± 4	46 ± 8
Object	-	-
Down	28 ± 1	33 ± 1
Ahead	14 ± 1	21 ± 7

NB, '-' indicates no fixation. The RP-cane participant did not look at the object in any of the trials. Only upon contact with the *Object* did the individual reorientate gaze to look down within the walkway. A large proportion of the trial was spent looking at the floor outside of the walkway. Data presented are the mean ± SD.