

# Stable Individual Differences Across Images in Human Saccadic Eye Movements

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Individual differences in eye movements during picture viewing were examined across image format, content, and foveal quality in 3 experiments. Experiment 1 demonstrated that an individual's fixation durations were strongly related across 3 types of scene formats and that saccade amplitudes followed the same pattern. In Experiment 2, a similar relationship was observed for fixation durations across faces and scenes, although the amplitude relationship did not hold as strongly. In Experiment 3, the duration and amplitude relationships were observed when foveal information was degraded and even removed. Eye movement characteristics differ across individuals, but there is a great deal of consistency within individuals when viewing different types of images.

*Keywords:* eye movements, individual differences, visual perception cognitive processes

Individual differences are often observed in experiments that examine saccadic eye movements in complex visual tasks like reading and picture viewing (Buswell, 1935; Henderson & Hollingworth, 1998, 1999; Rayner, 1998; Yarbus, 1967). These individual differences could be due to random variability or could reflect systematic endogenous factors that differ across individuals but are relatively stable within an individual from one viewing situation to another. To what degree are these differences stable within an individual across viewing situations? In a recent study, Andrews and Coppola (1999) had participants view five different visual stimuli under passive or active viewing tasks. Passive tasks included looking in the dark, viewing simple visual patterns, and viewing photographed scenes. For both dark and simple pattern conditions, participants were instructed to keep their gaze forward. In the scene condition, participants were instructed to look "as though viewing the scene in real life." Active tasks included a visual search task and reading. The visual search task involved searching "Where's Waldo?" images. In the reading task, participants read one passage extracted from various sources (ranging from biochemistry to a children's novel). Participants' fixation durations and saccade amplitudes were correlated within the active

and passive tasks, but there was very little correlation across the task types. They concluded that there were endogenous sources of variance that could be found in eye movement patterns within a task type.

The degree to which basic oculomotor measures reflect reliable individual differences is important for two reasons. First, if the variability observed in eye movement measures is due to endogenous factors, then this variability cannot be accounted for by eye movement control models that only incorporate exogenous factors. Second, reliable individual differences in eye movement measures would be of interest to investigators concerned with the potential neural substrates underlying eye movement control. For example, it has been suggested that an individual's ability to generate a saccadic eye movement in a direction opposite to a cue serves as an index of inhibitory function in prefrontal cortex (Guitton, Bachtel, & Douglas, 1982, 1985). Performance on the antisaccade task is correlated with frontal lobe damage associated with dementia, normal aging, and attention deficit/hyperactivity disorder (Butler, Zacks, & Henderson, 1999; Currie, Ramsden, McArthur, & Maruff, 1991; Kane, Bleckley, Conway, & Engle, 2001; Nigg, Butler, Huang-Pollock, & Henderson, 2002). More complex saccadic eye movement patterns observed during scene exploration and visual search have also been used with some success to investigate prefrontal deficits associated with executive planning and inhibitory processes in schizophrenia and attention deficit/hyperactivity disorder (Karatekin & Asamow, 1998, 1999). The use of eye movement measures in this way critically depends on their psychometric properties: They must vary across individuals and be consistent within an individual; that is, they must be psychometrically reliable.

In the present study, we sought to investigate the stability of individual differences in eye movement behavior by examining the degree to which an individual's average fixation duration and average saccade length for one type of image predicts that individual's average fixation duration and average saccade length in another viewing situation.

As reviewed above, research has shown that eye movement guidance is influenced by cognitive factors (Henderson &

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Hollingworth, 1999; Rayner & Pollatsek, 1992) and that these factors may change over time as exploration continues and more information about the stimulus is acquired (Antes, 1974; Buswell, 1935; Loftus, 1983; also see Nodine, Carmody, & Kundel, 1978). In the present study, we also sought to investigate how endogenous differences inherent in the individual viewer vary over time. For instance, it is possible that early during viewing, fixation is influenced by stimulus properties more than by endogenous individual factors. In this case, we would expect a stronger relationship for fixations and saccades made during later exploration of the stimulus than those made in the initial stages of exploration.<sup>1</sup>

In the first experiment, the visual format in which pictures of scenes were presented was varied. The scenes were shown as black-and-white line drawings, color renderings of scenes created from wire-frame models, and full-color photographs. In the second experiment, the content of the image was manipulated more dramatically; pictures of faces were compared with pictures of scenes. In the third experiment, foveal information was systematically removed from the image through the creation of an artificial scotoma that was tied to the position of fixation. If individual differences in eye movements are based on stable endogenous oculomotor control settings idiosyncratic to the individual, then these differences should hold across viewing situations.

### Experiment 1

In Experiment 1, participants examined images of scenes in anticipation of a memory test (see Henderson, Weeks, & Hollingworth, 1999; Loftus & Mackworth, 1978). Images were presented in one of the following three formats: black-and-white line drawings, three-dimensional (3D) rendered color images, and full-color photographs. In each case, the images depicted real-world scenes.

#### Method

*Participants.* Eight Michigan State University undergraduate students took part in this experiment. All participants had normal vision that did not require corrective eyewear (contact lenses or eyeglasses), were naive with respect to the purpose of the research, and received partial credit for their introductory psychology courses.

*Stimuli and apparatus.* Thirty images of complex, real-world scenes were used as stimuli, 10 exemplars of each of three image formats. The image formats were line drawings, full-color renderings of 3D models of scenes, and full-color photographs. The three image formats were roughly similar in semantic content and depicted natural and manmade complex real-world scenes. The color photographs and line drawings depicted the same 10 categories of scenes, and the rendered images depicted rooms in a house.

The line drawings were modified from those used in prior experiments (Henderson et al., 1999; van Diepen & De Graef, 1994) and were created by photographing scenes in the environment and then tracing the primary contours of the images to produce line drawings. The photographs were taken from a variety of sources, including commercial photographic collections and our own photographs. The rendered scenes were created from commercially available 3D models and were rendered using 3D Studio Max as described in Henderson and Hollingworth (1999). The three image types subtended a visual angle of  $10^\circ \times 14.5^\circ$  (height  $\times$  width) at a viewing distance of 1.13 m.

The stimuli were displayed at a resolution of  $800 \times 600$  pixels on an NEC Multisync XE 15 monitor driven by a Hercules Dynamite Pro super videographics adapter card. The screen refresh rate was 100 Hz. The colors present on the monitor varied with the type of stimulus being shown; the line drawings were black-and-white drawings, and the photographs and rendered scenes were presented in full color. The contours of the line drawings appeared black (pixels off) against a gray (pixels on) background (the gray was created by setting the red, green, and blue channels to an intensity value of 16, whereas white is an intensity value of 64 on each channel). The photographs and rendered scenes were displayed at a color depth of 8 bits (256 colors). The room was illuminated by a low-intensity, indirect light source.

Eye movements were monitored using a Generation 5.5 Stanford Research Institute Dual Purkinje Image Eyetracker (Crane, 1994; Crane & Steele, 1985), which has a resolution of  $1'$  of arc and a linear output over the range of the visual display used. A bite-bar and forehead rests were used to maintain the participant's viewing position and distance. The position of the right eye was tracked, although viewing was binocular. Signals were sampled from the eyetracker using the polling mode of the Data Translations DT2802 analog-to-digital converter, producing a sampling rate of better than 1000 Hz. The eyetracker and display monitor were interfaced with a microcomputer running a 90-MHz Pentium processor. The computer controlled the experiment and maintained a complete record of time and eye position values over the course of each trial.

*Procedure.* Participants were instructed that their eye movements would be monitored while they looked at scenes that they would later be asked to distinguish from new scenes in which only a small detail of a particular object may have been changed (Henderson et al., 1999; Loftus & Mackworth, 1978). The memory test was never given. Participants were also informed that they would be shown each scene for 15 s.

Calibration of the eyetracker consisted of fixating four calibration markers at the top, bottom, left, and right sides of the display area. Calibration was checked by displaying a calibration screen consisting of six test positions and a fixation marker that indicated the computer's estimate of the current fixation position. The participant fixated the test positions, and if the fixation marker was within  $\pm 5'$  arc of each test marker, calibration was considered accurate. Once calibrated, the participant took part in three practice trials, one in each of the image conditions, using scenes that were not included in the experiment. The eyetracker was then recalibrated, and the participant was shown the 30 experimental trials.

A trial consisted of the following events. First, the calibration screen was shown and calibration was checked. The eyetracker was recalibrated whenever calibration was deemed inaccurate. Following the calibration check, the participant fixated on the centre marker to indicate that he or she was ready for the trial to begin. The experimenter then started the trial: The trial scene replaced the fixation display, and the scene remained visible for 15 s before being replaced by the calibration screen.

A given participant saw all 30 images, 10 of each type, in a random order that was determined individually for each viewer. The entire experiment lasted approximately 45 min.

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## Results

Following, we correlated eye movement measures across viewing conditions to index systematic individual differences in eye movement behaviour (Andrews & Coppola, 1999). We set alpha to .05 for all comparisons in the experiments. Table 1 summarises the results of Experiment 1.

Saccades were defined using a velocity criterion, and fixations were defined as periods of stability between saccades (see Henderson, McClure, Pierce, & Schrock, 1997). Fixation durations less than 90 ms were removed from the analyses to eliminate fixation artefacts resulting from the sensitivity of the dual-Purkinje image eyetracker. Mean fixation duration for each participant was computed for each condition across stimuli and trials. Correlations were generated using each participant's mean on each pair of stimulus types. The results indicated that there was a strong relationship for mean fixation durations for individuals across all stimulus types (see Figure 1): line drawing versus photograph,  $r = .97$ ,  $F(1, 6) = 91.36$ ,  $p < .01$ ; line drawing versus rendered scene,  $r = .93$ ,  $F(1, 6) = 40.63$ ,  $p < .01$ ; and rendered scene versus photograph,  $r = .94$ ,  $F(1, 6) = 48.77$ ,  $p < .01$ .

Saccade amplitudes were computed as the distance in degrees of visual angle between consecutive fixations. A strong correlation between mean saccade amplitudes was observed across all stimulus types (see Figure 2): line drawing versus rendered scene,  $r = .93$ ,  $F(1, 6) = 37.38$ ,  $p < .01$ ; line drawing versus photograph,  $r = .96$ ,  $F(1, 6) = 78.43$ ,  $p < .01$ ; and rendered scene versus photograph,  $r = .98$ ,  $F(1, 6) = 117.48$ ,  $p < .01$ .

Table 1  
Mean, Standard Deviation, and Range for Fixation Duration and Saccade Length in Experiment 1

Condition	<i>M</i>	<i>SD</i>	Range
<b>Line drawing</b>			
Fixation duration (ms)	348.02	50.70	279.61–421.55
First 5 fixations	319.95	53.34	251.36–413.12
Last 5 fixations	330.66	48.20	252.82–399.18
Saccade length (degrees)	2.39	0.48	1.69–3.12
First 5 saccades	1.77	0.43	0.99–2.37
Last 5 saccades	2.26	0.57	1.52–3.18
Initial saccade latency (ms)	388.64	125.67	308.80–659.90
Initial saccade length (degrees)	1.71	0.66	0.70–2.70
<b>Photo</b>			
Fixation duration (ms)	367.75	66.60	282.42–491.59
First 5 fixations	356.45	69.26	260.32–476.36
Last 5 fixations	364.57	78.56	279.12–481.30
Saccade length (degrees)	2.38	0.57	2.98–1.41
First 5 saccades	1.74	0.52	0.81–2.28
Last 5 saccades	2.26	0.74	0.76–2.87
Initial saccade latency (ms)	414.46	201.45	294.20–893.00
Initial saccade length (degrees)	1.96	0.71	1.18–3.04
<b>3D render</b>			
Fixation duration (ms)	336.87	43.42	276.20–408.45
First 5 fixations	320.49	53.38	253.10–397.80
Last 5 fixations	341.65	52.94	273.62–407.76
Saccade length (degrees)	2.50	0.59	1.51–3.33
First 5 saccades	1.71	0.49	0.89–2.37
Last 5 saccades	2.34	0.79	1.07–3.56
Initial saccade latency (ms)	383.43	106.17	285.10–632.20
Initial saccade length (deg)	1.92	0.54	1.15–2.64

Note. 3D = three dimensional.

It is not known whether an individual's mean fixation duration and mean saccade amplitude during scene viewing are systematically related. To examine this question, individuals' mean fixation duration and mean saccade amplitude were correlated within each stimulus type. No significant correlations were found in any of the three comparisons: line drawings ( $r = -.11$ ,  $F < 1$ ), photographs ( $r = -.19$ ,  $F < 1.5$ ), and rendered scenes ( $r = -.08$ ,  $F < 1.5$ ). Thus, there was no evidence that individuals' fixation durations were related to their saccade amplitudes.

As discussed above, past studies have shown that early exploratory eye movements may be largely governed by stimulus properties (Antes, 1974; Buswell, 1935; Loftus, 1983; also see Nodine et al., 1978). To investigate the nature of individual differences in eye movement behaviour over time, the average fixation duration and saccade length for each individual for the first five and last five fixations were analysed. The means are presented in Table 1. The results show that the relationship between fixation durations made early on in one format are closely tied to the early fixation durations in another for any single individual. For instance, there remained a strong correlation between average early fixations made on line drawings and photographed scenes, as well as rendered scenes,  $r = .92$ ,  $F(1, 6) = 32.62$ ,  $p < .01$ , and  $r = .95$ ,  $F(1, 6) = 54.4$ ,  $p < .01$ , respectively. The same is true for the relationship between rendered scene and photograph,  $r = .87$ ,  $F(1, 6) = 18.43$ ,  $p < .01$ . When fixations made during the later part of the viewing period were analysed, these strong correlations were still present, line drawing and photograph,  $r = .94$ ,  $F(1, 6) = 48.19$ ,  $p < .01$ ; line drawing and rendered scene,  $r = .91$ ,  $F(1, 6) = 27.39$ ,  $p < .01$ ; and rendered scene and photograph,  $r = .83$ ,  $F(1, 6) = 13.72$ ,  $p < .01$ , suggesting that fixations made in the early part of the viewing period reflect the same individual tendencies as later fixations.

The correlations for early and late saccades were also analysed. The results across stimulus formats showed a different pattern. Saccade lengths during the early part of the viewing pattern showed a slightly weaker relationship than saccade lengths made during the latter part. For instance, line drawing versus photograph showed a weak correlation early,  $r = .64$ ,  $F(1, 6) = 4.34$ ,  $p = .082$ , that was stronger toward the end,  $r = .79$ ,  $F(1, 6) = 10$ ,  $p < .01$ . This pattern was repeated for the line drawing and rendered scene early,  $r = .81$ ,  $F(1, 6) = 11.48$ ,  $p < .05$ , versus late,  $r = .94$ ,  $F(1, 6) = 47.9$ ,  $p < .01$ . The correlations were weaker when comparing photographs and rendered scenes, and the relation was stable across early saccades,  $r = .84$ ,  $F(1, 6) = 14.98$ ,  $p < .05$ , and late saccades,  $r = .83$ ,  $F(1, 6) = 12.65$ ,  $p < .05$ . These results suggest that in the case of differing scene formats, individual differences in average fixation duration and saccade length are stable over the course of the viewing period.

To examine more closely the possibility that individual differences are diminished and fixations more strongly influenced by stimulus properties in the initial phase of exploration, the latency to launch the first saccade (initial saccade latency) and the distance and direction of the first saccade were examined. The initial saccade latency was calculated as the time from the onset of the scene until the launch of the first saccade. The distance of the first saccade was calculated in degrees of visual angle from the fixation position at scene onset to the landing position of the first saccade. We found strong relationships for both initial saccade latency, line drawing and photograph,  $r =$

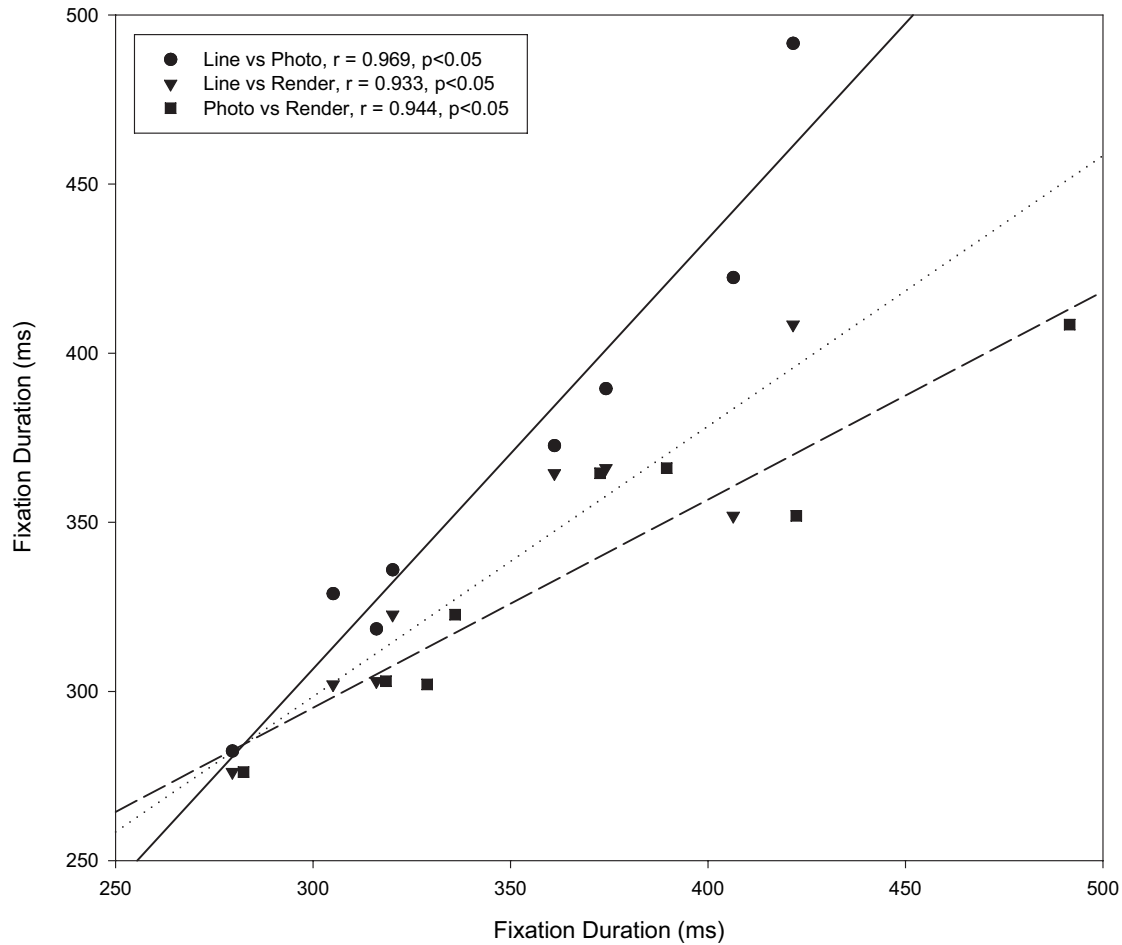


Figure 1. The correlations of fixation durations for each comparison of stimulus type in Experiment 1. Solid line = line drawing versus photograph; dotted line = line drawing versus rendered; dashed line = photograph versus rendered.

.97,  $F(1, 6) = 83.87$ ,  $p < .01$ ; line drawing and rendered scene,  $r = .91$ ,  $F(1, 6) = 29.84$ ,  $p < .01$ ; and rendered scene and photograph,  $r = .96$ ,  $F(1, 6) = 80.13$ ,  $p < .01$ , and for the distance of the first saccade, line drawing and photograph,  $r = .77$ ,  $F(1, 6) = 8.52$ ,  $p < .05$ ; line drawing and rendered scene,  $r = .89$ ,  $F(1, 6) = 23.63$ ,  $p < .01$ ; and rendered scene and photograph,  $r = .87$ ,  $F(1, 6) = 17.96$ ,  $p < .01$ . The direction of the initial saccade was calculated by dividing each scene into quadrants and recording the position of the fixation following the first saccade. The proportion of fixations in each quadrant for each individual was compared across the three stimulus formats. When we analysed the direction of the first saccade, weaker but significant correlations were found, line drawing and photograph,  $r = .43$ ,  $F(1, 6) = 6.82$ ,  $p < .05$ ; line drawing and rendered scene,  $r = .4$ ,  $F(1, 6) = 3.9$ ,  $p = .058$ ; and rendered scene and photograph,  $r = .49$ ,  $F(1, 6) = 9.24$ ,  $p < .05$ .

### Discussion

The results strongly indicated that two basic properties of eye movement behaviour, fixation durations and saccade amplitudes, are stable within individuals across image format during scene

viewing. At the same time, there was no relationship between an individual's fixation durations and saccade amplitudes, suggesting that the endogenous default values for these two aspects of oculomotor behaviour are independently determined. To examine possible shifts in individual oculomotor strategies over time, the first five and last five fixations were analysed. Significant correlations were found in all cases, although the fixation duration correlations were stable for the early fixations to the late fixations, whereas the saccade amplitude correlations tended to be stronger for later than for earlier saccades.

To further investigate the degree to which endogenous factors influence eye movements during the early exploratory phase of scene viewing, we examined three measures reflecting the initial eye movement made on a stimulus: latency of the first saccade and distance and direction of that saccade. We found correlations across stimulus types for all three measures, although those correlations were weaker for the distance and direction of the initial saccade. Overall, these data suggest that endogenous factors play a role in eye movements throughout the viewing period, although the amplitudes of early saccades may be less controlled by endogenous factors, perhaps because

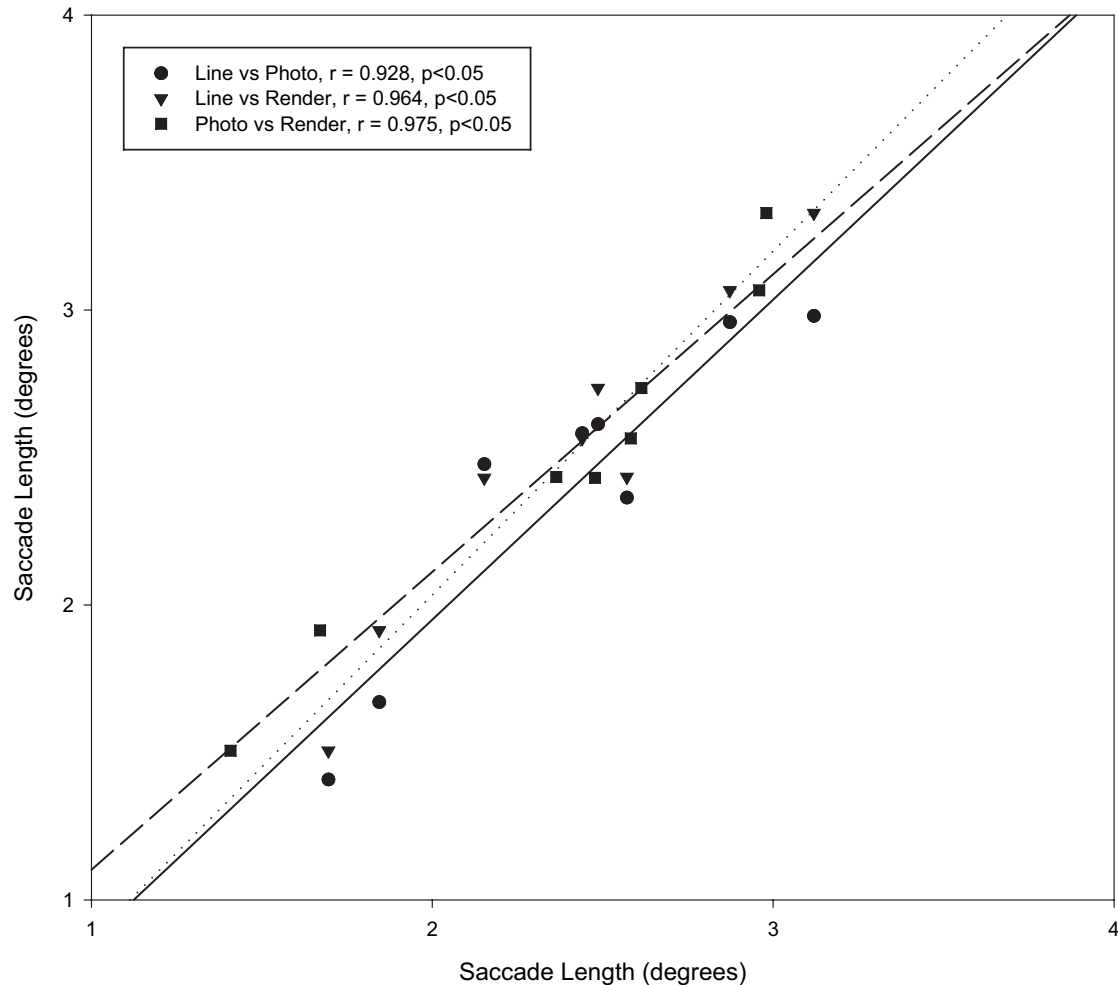


Figure 2. The correlations of saccade lengths for each comparison of stimulus type for Experiment 1. Solid line = line drawing versus photograph; dotted line = line drawing versus rendered; dashed line = photograph versus rendered.

they are more controlled by the stimulus. Once an initial exploratory phase is complete, individuals tend to rely more on their own oculomotor tendencies.

Although all the images in Experiment 1 depicted scenes, the visual properties of these images differed along many dimensions. For example, the line drawings were monochromatic and contained only contours, whereas the photographs were visually rich in detail. Despite these differences, and despite the fact that individuals differed in both their mean fixation durations and mean saccade amplitudes, there was strong consistency in how long a given individual's fixation durations lasted and how far that individual's eyes moved from one image type to another.

It might be argued that scenes are highly similar despite differences in format. To provide an additional test of eye movement consistency, Experiment 2 compared two qualitatively different stimulus types, scenes and faces.

## Experiment 2

In Experiment 2, image content was manipulated by using photographs depicting real-world scenes and human faces. View-

ing time and image medium (photograph) were held constant. If the results of Experiment 1 were caused by the similarity of the content of the images, then these effects should disappear in Experiment 2. If instead the effects were due to stable endogenous oculomotor factors that are at least partially independent of image content, then similar effects should be observed in Experiment 2.

## Method

**Participants.** Sixteen members of the Michigan State University undergraduate participant pool participated in this experiment. All participants had normal vision, were naive with respect to the purpose of the research, and received course credit for taking part in the experiment.

**Stimuli and apparatus.** The faces depicted 40 different female undergraduate students (approximately the same age) from Michigan State University and were obtained by taking their pictures with a digital camera under similar lighting conditions. All women were Caucasian and had dark hair that was cropped to a similar style using commercial graphics-editing software. None of the faces had any overly distinguishing characteristics such as ear-



rings, nose rings, or excessive make-up. All faces had the same neutral expression. Full-colour photographs of faces were cropped to  $400 \times 300$  pixels in size and were pasted into an  $800 \times 600$  grey background. The scenes were 10 full-colour photographs depicting indoor and outdoor environments. See Figure 3 for a sample face and scene. The apparatus was the same as was used in Experiment 1, and calibration was as described in Experiment 1.

**Procedure.** The procedure was similar to that used in Experiment 1, with the exception of the instructions. Participants were told that they were going to see a series of faces and scenes that they should study as carefully as possible to prepare for a memory test that would be administered later in the experiment. For the face-viewing task, the 20 faces were presented individually in the centre of the screen for 10 s each. For the scene-viewing task, the 10 scenes were presented individually for 10 s each. The entire experiment lasted approximately 35 min.

## Results

Analysis of the eye movement data was conducted as described in Experiment 1 (see Table 2 for summary of the results). Correlations of individual mean fixation durations across the two stimulus types

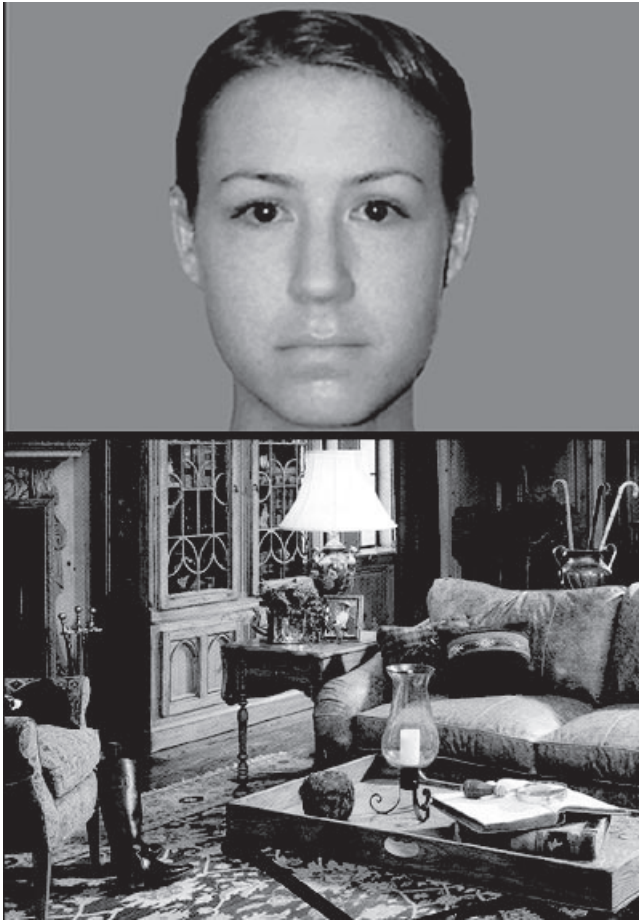


Figure 3. An example face and an example scene used in Experiment 2. Scene stimuli were presented in full color during the experiment. Faces were also presented in full colour on a grey background.

Table 2  
Mean, Standard Deviation, and Range for Fixation Duration and Saccade Length in Experiment 2

Condition	<i>M</i>	<i>SD</i>	Range
<b>Faces</b>			
Fixation duration (ms)	322.56	46	246.33–391.89
First 5 fixations	267.29	45.55	188.9–378.48
Last 5 fixations	369.16	78.9	253.3–582.56
Saccade length (degrees)	2.09	0.27	1.69–2.72
First 5 saccades	2.12	0.26	1.51–2.46
Last 5 saccades	1.93	0.28	1.54–2.35
Initial saccade latency (ms)	209.22	55.49	135.7–355.15
Initial saccade length(degrees)	1.4	0.35	1.0–2.1
<b>Scenes</b>			
Fixation duration (ms)	295.85	38.9	237.29–370.06
First 5 fixations	252.63	37.5	193.84–332.34
Last 5 fixations	328.96	71.34	223.3–474.4
Saccade length (degrees)	3.27	0.43	2.58–4.23
First 5 saccades	2.83	0.4	2.05–3.95
Last 5 saccades	3.29	0.6	2.33–4.33
Initial saccade latency (ms)	210	42.65	148.9–299.2
Initial saccade length(degrees)	2.9	0.66	1.48–4.0

showed that participants' fixation durations were stable,  $r = .75$ ,  $F(1, 14) = 17,871.96$ ,  $p < .01$ , despite the differences in average fixation durations across participants (see Figure 4). This finding demonstrates that fixation duration remains relatively stable within an individual even when the contents of the viewed images differ dramatically.

The correlation for saccade amplitudes across faces and scenes was not significant, although there was a trend toward a positive correlation ( $r = .27$ ;  $F < 1.2$ ; see Figure 5). One possible explanation for the lack of a statistically significant correlation for saccade amplitudes is that there were fewer potential saccade targets in the faces than in the complex scenes, leading to less variability in saccade amplitudes in the faces. In fact, the majority (about 80%) of all fixations on the faces were on the eyes (see Henderson, Falk, Minut, Dyer, & Mahadevan, 2001; Henderson, Williams, & Falk, 2005). Figure 6 depicts the frequency distribution of saccade amplitudes for faces and scenes, indicating that there were fewer longer saccades for faces than scenes.

As in Experiment 1, correlations were computed to investigate the relationship between fixation duration and saccade amplitude. This analysis showed that the two were independent of one another (faces:  $r = -.03$ ,  $F < 1$ ; scenes:  $r = .32$ ,  $F < 1.5$ ), corroborating the findings from Experiment 1. However, this analysis must be treated with caution given the failure to find an overall stable effect of saccade amplitude across images.

The stability of endogenous oculomotor control for fixation durations and saccade lengths were analysed for early and late fixations as was done in Experiment 1. Again, the first five and last five fixations were calculated and compared. Unlike in Experiment 1, the durations of early fixation were clearly less influenced by individual oculomotor strategies,  $r = .55$ ,  $F(1, 14) = 6.11$ ,  $p < .05$ , than were later fixations,  $r = .78$ ,  $F(1, 14) = 21.57$ ,  $p < .01$ . This pattern was mimicked when saccade length was compared for early and late fixations. Results showed that the correlation between face and scene stimuli was weaker still for early saccades,  $r = .21$ ,  $F < 1$ , than later saccades,  $r = .46$ ,  $F(1, 14) = 3.74$ ,  $p = .07$ .

The results support the hypothesis that individual oculomotor strategies are more influential on eye movement patterns during the later

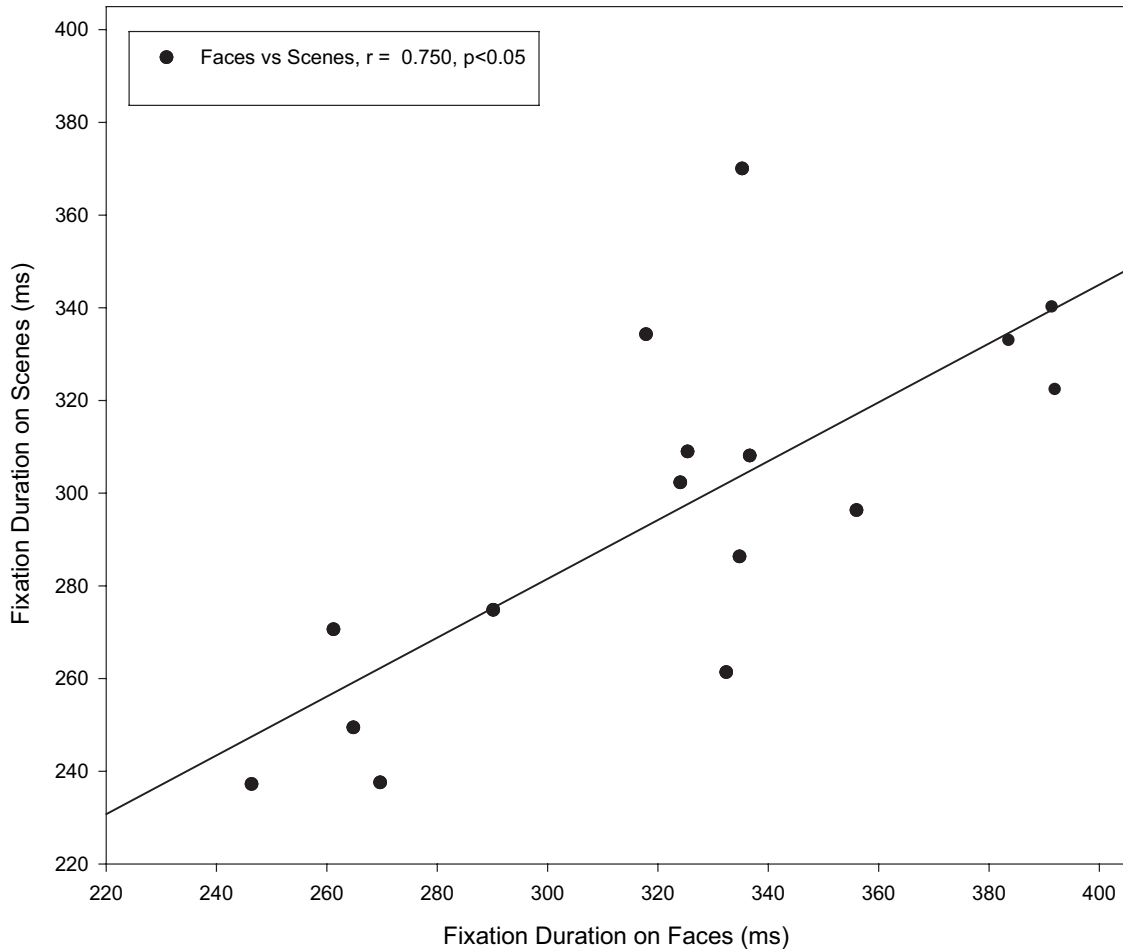


Figure 4. The correlation of average fixation duration for faces and scenes in Experiment 2. Each symbol represents 1 participant's average fixation duration for each stimulus type.

part of the viewing period. Further support for this hypothesis was found when the initial fixation measures were analysed. The initial saccade latency,  $r = .26$ ,  $F < 1$ ; the initial saccade amplitude,  $r = .22$ ,  $F < 1$ ; and the initial saccade direction,  $r = .34$ ,  $F(1, 14) = 7.33$ ,  $p < .01$ , showed the same weak correlations between the initial fixation on the face and scene stimuli. However, it should be noted that the range limitations discussed above for the overall saccade amplitude also apply to the initial saccade measures.

### Discussion

The results from Experiment 2 further support the hypothesis that individuals produce relatively stable eye movement behaviour across viewing conditions. Specifically, as in Experiment 1, the results of Experiment 2 showed that there was a strong relationship between an individual's fixation durations across scenes and faces. This finding is striking because one might have expected strong exogenous control effects for faces, a stimulus for which processing appears to be driven by an independent cognitive module.

However, in contrast to Experiment 1, there was a weaker and statistically nonsignificant relationship between the average saccade amplitude of an individual across faces and scenes. Given that viewers

tend to restrict their fixations to the four salient features of a face (two eyes, nose, and mouth), with the vast majority of these fixations on the eyes (Altoff & Cohen, 1999; Henderson et al., 2001, 2005; Mertens, Siegmund, & Gruesser, 1993; Walker-Smith, Gale, & Findlay, 1977), it is not surprising that saccade amplitudes would be less related across faces and scenes than they are across different depictions of scenes. Nevertheless, despite this caveat, fixation durations within individuals remained stable across faces and scenes.

It is interesting to note that we did see similar patterns of differences between the initial fixations and later fixations in Experiment 2 as those seen in Experiment 1, consistent with the hypothesis that at the beginning of the viewing period there is a weaker influence of endogenous oculomotor tendencies for an individual. However, there were also some notable differences across experiments. In Experiment 1, changes in the strengths of the relationships arose in the saccade amplitude of the early versus late fixations, as well as the latency, amplitude, and direction of the initial fixation. In Experiment 2, the change was seen with fixation durations and with saccade amplitude. Given the restriction of range (as discussed above) and the tendency for participants to focus on the eyes when viewing face stimuli (see Henderson et al., 2005), it is not surprising that the

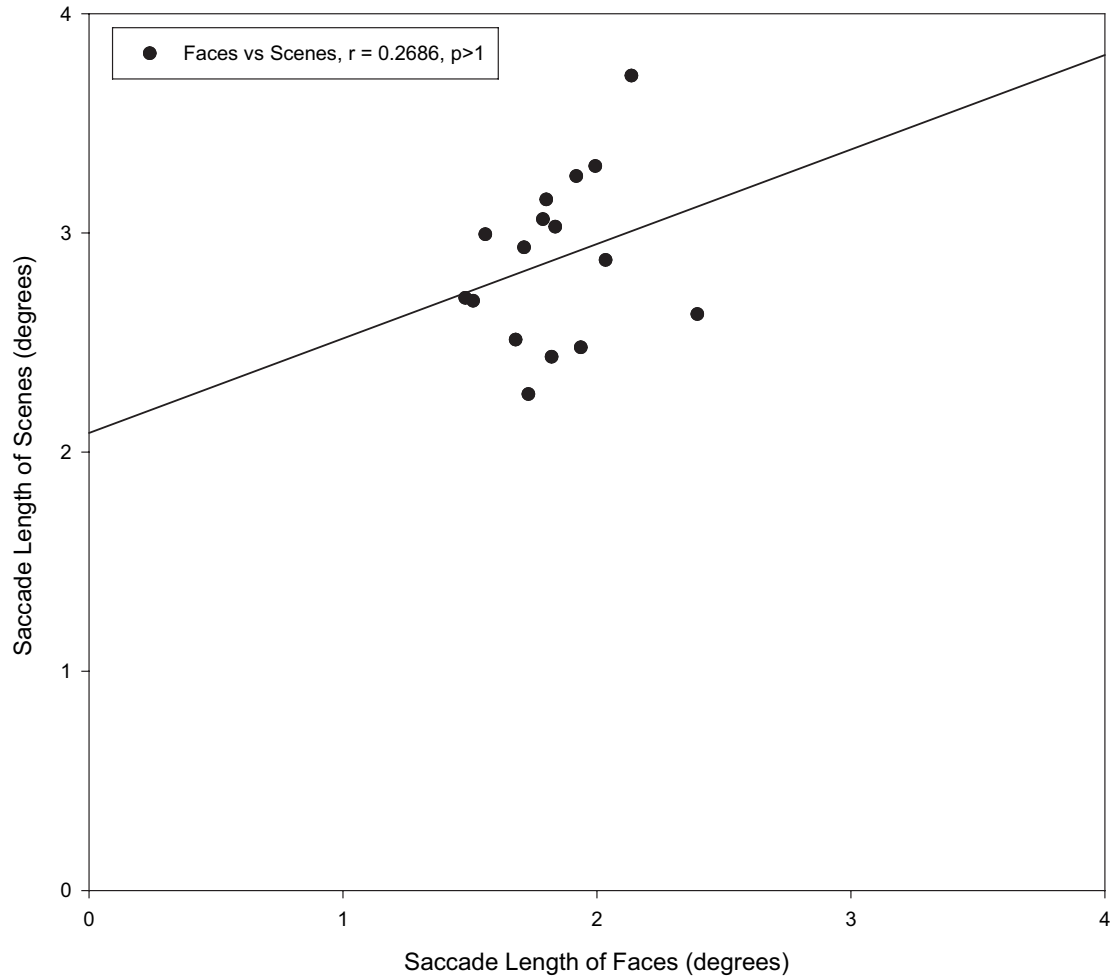


Figure 5. The correlation of average saccade amplitude for faces and scenes in Experiment 2. Each symbol represents 1 participant's average saccade amplitude for each stimulus type.

correlations of initial saccade amplitudes failed to reach statistical significance. It is important to note, however, that these endogenous influences are not completely abolished within the first few fixations and that despite the highly structured examination of the faces, these endogenous oculomotor strategies continued to exert some influence in the pattern of fixation durations.

If the correlations observed in Experiments 1 and 2 were due to similarities across image properties at fixation, then systematically removing the fixated information in the images should eliminate the correlations. This possibility was examined in Experiment 3 by using a fixation-contingent moving artificial foveal scotoma to manipulate the information available at the fovea during each fixation.

### Experiment 3

In Experiment 3, the influence of foveal visual information on the consistency of an individual's eye movements was examined. An artificial scotoma was used to degrade, to varying extents, visual information at the fovea. Fixation durations and saccade amplitudes for individuals were correlated across the degree to which the image was degraded by the artificial scotoma.

### Method

*Participants.* Fifteen participants from the Michigan State University undergraduate participant pool were recruited for this experiment. All participants had normal vision, were naive with respect to the purpose of the research, and received course credit for taking part in the experiment.

*Stimuli and apparatus.* Forty<sup>2</sup> digitised colour photographs of real-world scenes were selected from Web pages, magazines, and books, with the constraint that there be no people or recognisable writing in them.

A moving artificial scotoma tied to eye position was used to restrict the amount of information available at the fovea. The scotoma was circular and subtended 2° of visual angle in diameter. Outside the scotoma, the image appeared normal, whereas inside the scotoma the scene was altered according to condition. In the

<sup>2</sup> The experiment included a control condition in which a ring surrounding the area occupied by the scotoma was shown in the place of a scotoma. Because we are interested in the question of what happens as the incoming



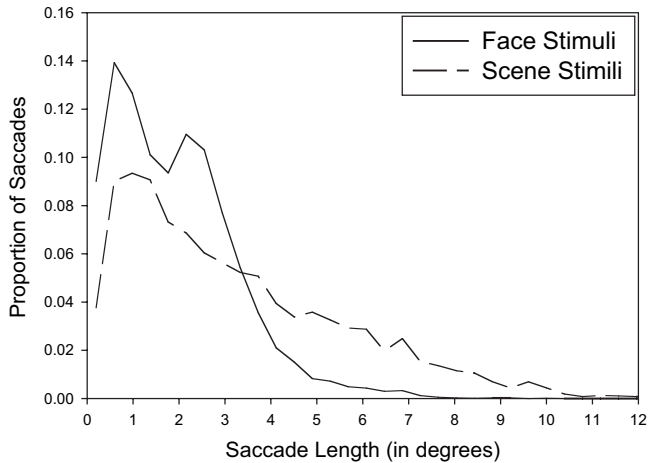


Figure 6. Saccade amplitude frequency distributions for faces and scenes in Experiment 2.

0% (free viewing) control condition, the scene was unaltered. In the 33%, 66%, and 100% scotoma conditions, the scene was degraded within the scotoma by replacing the corresponding percentage of randomly selected scene pixels with grey pixels. For the 33% and 66% conditions, the pixels were randomly selected at the beginning of each trial according to the scotoma condition, and those selected pixel positions within the scotoma remained occluded for the remainder of the trial. The apparatus used in Experiments 1 and 2 was also used in Experiment 3.

**Procedure.** Participants were instructed and calibrated as in Experiments 1 and 2. Participants were also told that some of the scenes would appear distorted in some way and to ignore these distortions as best they could and concentrate on studying the scenes. Each participant viewed each scene once for a maximum of 15 s, and the scenes were counterbalanced across conditions and participants so that each scene was presented an equal number of times in each condition. The four scotoma conditions were randomised throughout the study session, with only one condition taking place in a single trial.

## Results

The data for Experiment 3 are summarised in Tables 3 (fixation duration) and 4 (saccade length). Mean fixation duration and mean saccade amplitude was computed for each participant in each viewing condition. The primary analyses focused on correlating the 0% scotoma condition (free viewing) and the 100% scotoma condition (complete scotoma) with the partial scotoma conditions.

The fixation duration correlation analyses for free viewing in comparison with the other conditions revealed all correlations to be significant: 0% and 33%,  $r = .54$ ,  $F(1, 13) = 5.40$ ,  $p < .05$ ; 0% and 66%,  $r = .56$ ,  $F(1, 13) = 5.89$ ,  $p < .05$ ; and 0% and 100%,  $r = .63$ ,  $F(1, 13) = 8.36$ ,  $p < .05$ . The correlation analyses for the complete scotoma versus the partial scotoma conditions were also significant: 100% and 66%,  $r = .87$ ,  $F(1, 13) = 39$ ,  $p < .01$ , and 100% and 33%,  $r = .66$ ,  $F(1, 13) = 10.04$ ,  $p < .01$ .

For the analysis of saccade amplitudes, the correlations again showed consistency across availability of foveal information. For the correlations of the free viewing and partial scotoma conditions,

Table 3  
Mean, Standard Deviation, and Range for Fixation Durations in Experiment 3

Condition	<i>M</i>	<i>SD</i>	Range
No scotoma			
Fixation duration (ms)	344.75	33.86	287.79–403.98
First 5 fixations	344.07	56.27	245.54–448.1
Last 5 fixations			
33% Scotoma	369.63	47.16	275.94–436.64
Fixation duration (ms)	402.86	52.84	313.15–500.21
First 5 fixations	388.5	70.98	272.32–527.76
Last 5 fixations	434.47	78.62	328.7–586.94
66% Scotoma			
Fixation duration (ms)	367.96	38.69	293.19–426.54
First 5 fixations	368.83	57.79	277.94–279.14
Last 5 fixations	407.62	61.03	295.22–487.86
100% Scotoma			
Fixation duration (ms)	340.87	44.62	276.4–431
First 5 fixations	341.54	51.27	279.14–441.74
Last 5 fixations	367.38	85.66	281.76–617.02

the results were 0% and 33%,  $r = .85$ ,  $F(1, 13) = 34.46$ ,  $p < .01$ ; 0% and 66%,  $r = .73$ ,  $F(1, 13) = 14.91$ ,  $p < .01$ ; and 0% and 100%,  $r = .68$ ,  $F(1, 13) = 11.19$ ,  $p < .01$ . For the 100% scotoma condition, there were similarly strong relationships with the partial scotoma conditions: 100% and 66%,  $r = .97$ ,  $F(1, 13) = 184.87$ ,  $p < .01$ , and 100% and 33%,  $r = .93$ ,  $F(1, 13) = 83.10$ ,  $p < .01$ .

The relationship between average saccade amplitude and average fixation duration for each individual was analysed for each condition, as in Experiments 1 and 2. No significant effects were found for 0%, 33% and 100% scotoma conditions, 0%:  $r = .22$ ,  $F < 1$ ; 33%:  $r = -.22$ ,  $F < 1$ ; and 100%:  $r = -.34$ ,  $F < 1.8$ . A significant relationship was observed for the 66% scotoma condition,  $r = -.51$ ,  $F(1, 13) = 4.62$ ,  $p < .05$ , but closer analysis of the data revealed that the correlation was driven by one outlier data point. When this point was removed from the analysis, the correlation disappeared,  $r = -.36$ ,  $F < 1.8$ . As found in the first two experiments, the results suggest that there is no systematic relationship between an individual's average fixation duration and that individual's average saccade amplitude.

The presence of a scotoma also poses an interesting question regarding how influential individual oculomotor strategies are during early versus later periods of viewing. On one hand, because the scotoma presents a challenge to extracting visual information that the participant must learn to work around, it is possible that oculomotor strategies will be less influential at the beginning of the trial not only because there is a strong influence of stimulus factors, but also because the system has to adapt to this new viewing situation. On the other hand, by blocking the availability of stimulus information at the centre of the visual field, it could be that oculomotor strategies will be more visible at the beginning of the trial and so the influence of individual oculomotor strategies will be stable across the viewing period. When we compared early with late fixations in the 0% scotoma and 33% scotoma conditions, we found that the correlations remained stable, with no remarkable

visual information is diminished, this condition is not discussed. Therefore, only 40 items are analysed for each participant.

Table 4  
Mean, Standard Deviation and Range for Saccade Length in  
Experiment 3

Condition	M	SD	Range
No scotoma			
Saccade length (degrees)	3.12	0.57	2.46–4.39
First 5 saccades	2.27	0.54	1.47–3.42
Last 5 saccades	2.95	0.64	1.79–4.35
Initial saccade latency (ms)	385.49	59.56	317–509.5
Initial saccade length	2.4	0.66	1.42–3.53
33% Scotoma			
Saccade length (degrees)	3.16	0.63	2.25–4.8
First 5 saccades	2.26	0.57	1.42–3.7
Last 5 saccades	3.18	0.75	2.33–4.99
Initial saccade latency (ms)	425.37	95.06	295.8–652.2
Initial saccade length	2.27	0.55	1.71–3.7
66% Scotoma			
Saccade length (degrees)	3.52	0.71	2.04–5.13
First 5 saccades	2.44	0.61	1.32–3.69
Last 5 saccades	3.38	0.92	1.9–5.48
Initial saccade latency (ms)	423.54	91.52	316.4–637.6
Initial saccade length	2.24	0.6	1.36–3.62
100% Scotoma			
Saccade length (degrees)	3.66	0.64	2.35–5.08
First 5 saccades	2.65	0.45	1.97–3.66
Last 5 saccades	3.56	0.87	2.16–5.73
Initial saccade latency (ms)	396.24	67.77	302.9–531.9
Initial saccade length	2.38	0.66	1.46–3.4

difference between the early,  $r = .64$ ,  $F(1, 13) = 9.16$ ,  $p < .01$ , and late periods,  $r = .59$ ,  $F(1, 13) = 7.0$ ,  $p < .01$ . This is reminiscent of the average fixation duration patterns seen in Experiment 1. The same pattern was observed for the other scotoma conditions, although the correlations were weaker and not statistically significant. The 66% scotoma condition produced almost identical correlation measures for the early,  $r = .44$ ,  $F(1, 13) = 3.04$ ,  $ns$ , and late viewing periods,  $r = .41$ ,  $F < 2.5$ . For the 100% scotoma condition, the same pattern was seen for early,  $r = .27$ ,  $F < 1$ , and late periods,  $r = .36$ ,  $F < 2$ . However, the pattern appears to be different when comparing the scotoma conditions. It seems that when a scotoma is present, the oculomotor strategies are more prevalent during the early part of the viewing period, 100% and 33%,  $r = .61$ ,  $F(1, 13) = 7.69$ ,  $p < .05$ ; 100% and 66%,  $r = .75$ ,  $F(1, 13) = 17.03$ ,  $p < .01$ , as compared with the later part of the viewing period, 100% and 33%,  $r = .5$ ,  $F(1, 13) = 4.39$ ,  $p = .056$ , and 100% and 66%,  $r = .69$ ,  $F(1, 13) = 12.1$ ,  $p < .01$ . This pattern suggests that without immediate availability of visual information, individual oculomotor strategies indeed play a greater role in the control of eye movements.

Further evaluation of the early part of the viewing period revealed that the effect of the scotoma on the initial saccade latency is less clear. Rather than a clear influence of individual oculomotor strategies, the correlations showed a mixed pattern. The 0% scotoma was significantly correlated with the 33% scotoma,  $r = .66$ ,  $F(1, 13) = 10$ ,  $p < .01$ , and 66% scotoma,  $r = .85$ ,  $F(1, 13) = 34.52$ ,  $p < .01$ , but not with the 100% scotoma,  $r = .39$ ,  $F(1, 13) = 2.3$ ,  $ns$ . The scotoma conditions revealed equally strong correlations with each other, 100% and 33%,  $r = .60$ ,  $F(1, 13) = 7.1$ ,  $p < .05$ , and 100% and 66%,  $r = .62$ ,  $F(1, 13) = 8.2$ ,  $p < .05$ . The initial saccade length, however, showed a pattern that mim-

icked the findings for the early viewing period, with a stronger relationship between the scotoma conditions, 100% and 33%,  $r = .60$ ,  $F(1, 13) = 6.4$ ,  $p < .05$ , and 100% and 66%,  $r = .75$ ,  $F(1, 13) = 16.5$ ,  $p < .01$ , than between the 0% scotoma condition and the other scotoma conditions, 0% and 33%,  $r = .43$ ,  $F(1, 13) = 3.8$ ,  $p = .075$ ; 0% and 66%,  $r = .48$ ,  $F(1, 13) = 3.9$ ,  $p = .068$ ; and 0% and 100%,  $r = .53$ ,  $F(1, 13) = 5.1$ ,  $p < .05$ . The pattern of correlations for the saccade direction revealed the same pattern for the scotoma conditions, 100% and 33%,  $r = .57$ ,  $F(1, 13) = 27.26$ ,  $p < .01$ ; 100% and 66%,  $r = .65$ ,  $F(1, 13) = 43.32$ ,  $p < .01$ , and for the 0% scotoma condition, 0% and 33%,  $r = .39$ ,  $F(1, 13) = 10.36$ ,  $p < .05$ ; 0% and 66%,  $r = .4$ ,  $F(1, 13) = 10.9$ ,  $p < .05$ ; and 0% and 100%,  $r = .44$ ,  $F(1, 13) = 13.8$ ,  $p < .05$ . This pattern of results suggests that when a scotoma blocks information at the fovea, individuals are more likely to be more influenced by endogenous oculomotor strategies not only in terms of the initial saccade's distance, but also in terms of its direction.

### Discussion

In Experiment 3, an artificial moving scotoma was used to obscure the amount of visual information available at the fovea. The stability of oculomotor behaviour was measured by correlating average fixation durations and saccade amplitudes for individuals across scotoma conditions. The correlations observed provide strong support for stable endogenous effects on basic eye movement behaviour. Interestingly, although the correlations tended to be smaller across the 0% and 100% scotoma conditions, they remained relatively robust and statistically significant. Foveal information is known to exert an influence on fixation durations (Rayner, 1998), yet even when this information was removed an individual's mean fixation duration was related to his or her mean fixation duration when complete foveal information was present. These results suggest that the observed correlations of previous experiments are not simply due to factors related to similarities in the foveal images across conditions.

Examination of the saccade amplitude frequency distributions for each scotoma condition (see Figure 7) shows that the majority of saccades were relatively short, with amplitudes less than 2° of

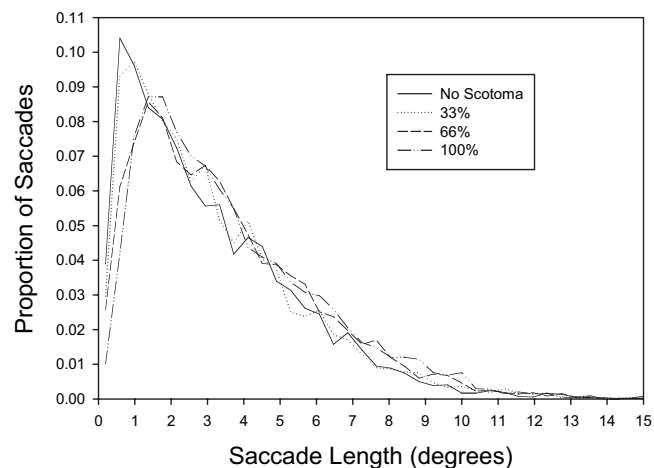


Figure 7. Saccade amplitude distributions for all conditions in Experiment 3.

visual angle.<sup>3</sup> In the partial and complete scotoma conditions, the scene image within 1° of the fixation point was distorted to some extent. Thus, in these conditions, the programming of a saccade to a target location within a 1° radius of fixation could not have been as influenced by the stimulus as would be the case under free viewing conditions. The distribution of saccade amplitudes reveals that as the information within the scotoma became more obscured, the proportion of short saccades (1° or less) decreased. Past studies examining both artificial and clinical scotoma populations have similarly shown that when a central scotoma occludes visual information at the fovea, viewers tend to develop strategies that maximise the information gained from outside the area of the scotoma (Cummings, Whittaker, Watson, & Budd, 1985; Whittaker, Budd, & Cummings, 1988; Whittaker, Cummings, & Swieson, 1991; White & Bedell, 1990). Yet, despite these changes in viewing strategy, the present study demonstrated that oculomotor behaviour within individuals remained relatively stable across conditions of foveal degradation.

Furthermore, in the case of the partial scotomas (33% and 66%), the grey pixels not only blocked foveal information, but could also create artificial contrasts or contours. As described above, the pixel placement in the partial scotomas was selected at the beginning of the trial and then remained fixed within the scotoma area for the remainder of the trial. As demonstrated by the increased correlations for the saccade length toward the later part of the viewing period, it seems that participants adapted to the interference of the partial scotomas. In addition, the pattern of increasingly stronger correlations toward the latter part of the viewing period suggests that with a scotoma, the individual may first have to adopt a strategy to acquire visual information, and so the influence of the stimulus may emerge later, allowing the endogenous strategies of the oculomotor system to be more influential during the early rather than the later part of the viewing period.

### General Discussion

Individual differences are typically observed in saccadic eye movement data collected from human viewers engaged in complex visual tasks. Andrews and Coppolla (1999) reported correlations for individuals' fixation durations and saccade amplitudes within active viewing tasks and within passive perceptual tasks, suggesting that endogenous factors play an important role in eye movement control. The results from "mindless reading" can similarly be taken to suggest that endogenous default control settings may account for some of the variability observed in reading (Vitu, O'Regan, & Inhoff, 1995). The present study introduced new data demonstrating that these consistencies within individuals are relatively stable across image format, image content, and image quality. In Experiment 1, a comparison of scenes shown in different formats (line drawings, colour renderings of 3D scene models, and colour photographs) showed remarkable individual consistency in average fixation duration and saccade amplitude, despite the wide range of average fixation durations and saccade amplitudes from 1 participant to the next. In Experiment 2, these results were extended to images with different content by comparing eye movements during viewing of pictures of faces and scenes. The results again revealed that fixation durations across faces and scenes were stable for each individual. However, most likely because of the restricted range of saccade amplitudes generated

during face viewing, only marginal correlations of saccade amplitudes were observed across faces and scenes. In Experiment 3, we used an artificial scotoma paradigm to investigate the influence of the foveal stimulus on the consistency of eye movement behaviour. We found that the oculomotor system showed consistent patterns within an individual across degrees of scotoma occlusion. Even when a change in viewing strategy was adopted by the viewer to acquire more visual information (by making longer saccades directed outside the image area covered by the scotoma), the correlations remained significant for both fixation duration and saccade amplitude. Finally, no systematic relationship between an individual's average fixation duration and average saccade amplitude was observed in the three experiments. These results suggest that the endogenous control settings for fixation duration and saccade amplitude within an individual are independently determined.

Across the three reported experiments, we also examined how the endogenous control settings change over the course of the viewing period. The results point to an interesting pattern of weaker correlations during the early part of the viewing period followed by stronger correlations toward the later part. This pattern fits with earlier studies of eye movements, showing that there is a stronger influence of stimulus properties during the initial processing of a new stimuli. When a scotoma blocked foveal information from view, the results showed a reversal in the pattern, with stronger correlations during the latter part of the viewing period among the conditions with a scotoma. These results support the notion that without immediate and full access to foveal information, the system had to adapt to this new viewing situation and rely more on its default settings during the beginning of the trial. The change in the correlations of an individual's fixation over time and across viewing situations serves to highlight the constant flux that the system is in as it balances incoming information and other ongoing cognitive processes. However, despite these constant changes, it seems that an individual's eye movement patterns demonstrate a constant underlying pattern.

It is important to note that the existence of a significant endogenous influence on fixation durations and saccade amplitudes does not in itself undermine the observation that visual and cognitive factors from the current fixation also exert an important influence on these eye movement behaviours. A substantial body of evidence demonstrates that saccadic eye movement behaviour is closely time locked to ongoing perceptual and cognitive processes during reading and picture perception (Henderson, 2003; Henderson & Ferreira, 2004; Rayner, 1998; see also Buswell, 1935; Tinker, 1946; Yarbus, 1967). For example, fixation durations and saccade amplitudes in reading are influenced by factors such as the lexical frequency, syntactic complexity, and discourse properties of the text (e.g., Birch & Rayner, 1997; Brysbaert & Mitchell, 1996; Carrithers & Bever, 1984; Ferreira & Henderson, 1990; Frazier & Rayner, 1982; Henderson & Ferreira, 1990; see Rayner, 1998). Studies have also shown that there is difference in the eye movement patterns of good versus poor readers, with good readers tending to make longer saccades and shorter fixations than poor readers (Eden, Stein, Wood, & Wood, 1994; Lefton, Nagle, John-

<sup>3</sup> The distributions were calculated by including all saccades from all participants in each of the conditions and the proportion of saccades was plotted as a function of degrees of visual angle.

son, & Fisher, 1979). Although there have been some attempts to directly link poor eye movement control as a cause of reading difficulties (Biscaldi, Gezeck, & Stuhr, 1998), these differences are thought to reflect the processing difficulties that poor readers have with words, and so they tend to spend more time on the material overall (Olson, Kliegl, & Davidson, 1983; Rayner, 1998). Although there were no measurements of comprehension in the current study, it would be interesting to investigate how endogenous control of eye movement patterns modulates stimulus processing. For instance, it is well known that with increased difficulty, fixations tend to become longer and saccades shorter as the individual devotes more processing time to any particular item. It would be interesting to see what happens to participants who tend to have long saccades: Do they revert to their natural tendencies and therefore become more likely to regress during reading than someone who naturally has a smaller saccade amplitude, for example? Future studies could investigate whether these individual tendencies for longer or shorter fixations are related to memory or comprehension of the stimuli. In addition, it would be interesting to investigate how these endogenous oculomotor strategies emerge over time as a participant gains experience with the stimuli.

Similarly, fixation durations and saccade lengths in picture perception are influenced by factors including familiarity, informativeness, and contextual appropriateness, as well as by viewing task (e.g., Antes, 1974; Buswell, 1935; Friedman, 1979; Henderson et al., 1999; Loftus & Mackworth, 1978; Saida & Ikeda, 1979; Yarus, 1967; see Henderson & Ferreira, 2004). A coupling between eye movement behaviour and perceptual and cognitive processing has also been demonstrated for a variety of complex perceptual-motor tasks such as spatial navigation, driving, sports activity including cricket batting and table tennis, and even during everyday activities like tea and sandwich making (Ballard, Hayhoe, & Pelz, 1995; Cutting, Alliprandini, & Wang, 2000; Land & Horwood, 1995; Land & Lee, 1994; Land & McLeod, 2000; Liu, 1998).

There are two ways in which both endogenous control settings and higher level visual and cognitive systems might combine to control saccadic eye movements. First, visual and cognitive influences may serve to modulate an underlying rhythm established by endogenous control. To make this point clear, we use an analogy to walking. Each person has a particular gait that determines among other things the spatial extent of each step and the rate at which these steps are generated. This gait is presumably determined by some combination of physical constraints (e.g., differences in leg length, muscle tone, and fitness), neural constraints (e.g., differences in perceptual and motor control systems in the brain), developmentally learned factors (e.g., tendency to lean or point at which weight is shifted), and perhaps general psychological constraints (e.g., personality characteristics, motivation) of the individual. Idiosyncratic gaits would presumably be stable across walking environments (e.g., on pavement, in mud, in snow) in the sense that individuals would tend to be rank ordered similarly from one environment to another. All of this suggests a stable idiosyncrasy in walking gait because of endogenous factors. However, in addition to these endogenous factors, one would also expect clear effects of exogenous factors on any given step. For example, a hole in the path would require a modification of the gait as it was encountered. Furthermore, the need to step over a small hole

would require less modification of the gait than the need to step over a larger bump. These holes can be seen as equivalent to the visual and cognitive obstacles that crop up in the course of natural visual cognition and that cause fixation durations to increase and saccade amplitudes to decrease. As in walking gait, such effects can be seen immediately. The existence of the gait does not undermine the existence of important and robust effects of obstacles on it. At the same time, the existence of robust visual and cognitive effects does not undermine the existence of an endogenously determined gait.

A second way to accommodate both endogenous control settings and the existence of higher level control on saccadic eye movement behaviour would be to give priority to visual and cognitive systems, but allow modulation of those systems by endogenous control settings. For example, it could be that at any given moment, the release of the current fixation and targeting of the impending saccade is determined by current activity in visual and cognitive systems. At the same time, these computations could be modulated by global control settings that bias the system to release the fixation or to select saccade targets at specific times and distances. Such a model reverses the priority given to visual and cognitive systems and global control settings, but would still account for an overall effect of control settings.

In summary, the results of the present study suggest that a complete theory of saccadic eye movement control in active vision will require an account of stable endogenous control settings and the stimulus and cognitive factors that have typically been considered.

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## Résumé

Au moyen de trois expériences, les différences individuelles des mouvements oculaires effectués pendant le visionnement d'une image ont été étudiées en fonction du format de l'image, de son contenu et de la qualité fovéale. L'expérience 1 a démontré que les durées de fixation étaient fortement liées aux trois types de scènes présentés et qu'il en était de même des amplitudes saccadiques. À l'expérience 2, on a observé un lien similaire pour ce qui est des durées de fixation des visages et des scènes, mais dans le cas de l'amplitude saccadique, le lien n'était pas aussi évident. Au cours de l'expérience 3, on a observé une relation entre la durée et l'amplitude lorsque l'information fovéale était dégradée, voire inexistante. Les caractéristiques du mouvement oculaire sont différentes d'une personne à l'autre, mais, dans le cas du visionnement de différents types d'images, elles présentent des similarités certaines.

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## References

- Altoff, R. R., & Cohen, N. J. (1999). Eye-movement-based memory effect: Reprocessing effect in face perception. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 997–1010.
- Andrews, T. J., & Coppola, D. M. (1999). Idiosyncratic characteristics of saccadic eye movements when viewing different visual environments. *Vision Research*, *39*, 2947–2953.
- Antes, J., R. (1974). The time course of picture viewing. *Journal of Experimental Psychology*, *103*, 62–70.
- Ballard, D. H., Hayhoe, M. M., & Pelz, J. B. (1995). Memory representations in natural tasks. *Journal of Cognitive Neuroscience*, *7*, 66–80.



- Birch, S., & Rayner, K. (1997). Linguistic focus affects eye movements during reading. *Memory & Cognition*, 25, 653–660.
- Biscaldi, M., Gezeck, S., & Stuhr, V. (1998). Poor saccadic control correlates with dyslexia. *Neuropsychologia*, 36(11), 1189–1202.
- Brysbaert, M., & Mitchell, D. C. (1996). Modifier attachment in sentence parsing: Evidence from Dutch. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 49A, 664–695.
- Buswell, G. T. (1935). *How people look at pictures: A study of the psychology of perception in art*. Chicago Press: Chicago.
- Butler, K. M., Zacks, R. T., & Henderson, J. M. (1999). Suppression of reflexive saccades in younger and older adults: Age comparisons on an antisaccade task. *Memory & Cognition*, 27, 584–591.
- Carrithers, C., & Bever, T. G. (1984). Eye-fixation patterns during reading confirm theories of language comprehension. *Cognitive Science*, 8, 157–172.
- Crane, H. D. (1994). The Purkinje image eyetracker, image stabilization, and related forms of stimulus manipulation. In D. H. Kelley (Ed.), *Visual science and engineering: Models and applications* (pp. 15–89). New York: Marcel Dekker.
- Crane, H. D., & Steele, C. M. (1985). Generation V dual-Purkinje-image eyetracker. *Applied Optics*, 24, 527–537.
- Cummings, R. W., Whittaker, S. G., Watson, G. R., & Budd, J. M. (1985). Scanning characters and reading with a central scotoma. *American Journal of Optometry and Physiological Optics*, 62, 833–843.
- Currie, J., Ramsden, B., McArthur, C., & Maruff, P. (1991). Validation of a clinical antisaccade eye-movement test in the assessment of dementia. *Archives of Neurology*, 48, 644–648.
- Cutting, J. E., Alliprandini, P. M. Z., & Wang, R. F. (2000). Seeking one's heading through eye movements. *Psychonomic Bulletin & Review*, 7, 490–498.
- Eden, G. E., Stein, J. E., Wood, H. M., & Wood, E. B. (1994). Differences in eye movements and reading problems in dyslexic and normal children. *Vision Research*, 34, 1345–1358.
- Ferreira, F., & Henderson, J. M. (1990). Use of verb information in syntactic parsing: Evidence from eye movements and word-by-word self-paced reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 555–564.
- Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, 14, 178–210.
- Friedman, A. (1979). Framing pictures—Role of knowledge in automated encoding and memory for gist. *Journal of Experimental Psychology: General*, 108, 316–355.
- Guitton, D., Bachtel, H. A., & Douglas, R. M. (1982). Disturbances of voluntary saccadic eye movement mechanisms following discrete unilateral frontal lobe removals. In G. Lennerstrand & E. L. Keller (Eds.), *Functional basis of ocular motility disorders* (pp. 497–499). Elmsford, NY: Pergamon Press.
- Guitton, D., Bachtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research*, 58, 455–472.
- Henderson, J. M. (2003). Human gaze control in real-world scene perception. *Trends in Cognitive Sciences*, 7, 498–504.
- Henderson, J. M., Falk, R., Minut, S., Dyer, F. C., & Mahadevan, S. (2001). Gaze control for face learning and recognition in humans and machines. In T. Shipley & P. Kellman (Eds.), *From fragments to objects: Segmentation processes in vision* (pp. 463–481). New York: Elsevier.
- Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty in the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 417–429.
- Henderson, J. M., & Ferreira, F. (2004). Scene perception for psycholinguists. In J. M. Henderson & F. Ferreira (Eds.), *The interface of language, vision, and action: Eye movements and the visual world* (pp. 1–58). New York: Psychology Press.
- Henderson, J. M., & Hollingworth, A. (1998). Eye movements during scene viewing: An overview. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 269–283). Oxford, England: Elsevier.
- Henderson, J. M., & Hollingworth, A. (1999). The role of fixation position in detecting scene changes across saccades. *Psychological Science*, 10, 438–443.
- Henderson, J. M., McClure, K., Pierce, S., & Schrock, G. (1997). Object identification without foveal vision: Evidence from artificial scotoma paradigm. *Perception & Psychophysics*, 59, 323–346.
- Henderson, J. M., Weeks, P. A., & Hollingworth, A. (1999). The effects of semantic consistency on eye movements during complex scene viewing. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 210–228.
- Henderson, J. M., Williams, C. C., & Falk, R. J. (2005). Eye movements are functional during face learning. *Memory & Cognition*, 33, 98–106.
- Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, 130, 169–183.
- Karatekin, C., & Asarnow, R. F. (1998). Components of visual search in childhood-onset schizophrenia and attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology*, 26, 367–380.
- Karatekin, C., & Asarnow, R. F. (1999). Exploratory eye movements to pictures in childhood-onset schizophrenia and attention-deficit/hyperactivity disorder (ADHD). *Journal of Abnormal Child Psychology*, 27, 35–49.
- Land, M. F., & Horwood, J. (1995, November 23). Which parts of the road guide steering. *Nature*, 377, 339–340.
- Land, M. F., & Lee, D. N. (1994, June 30). Where we look when we steer. *Nature*, 369, 742–744.
- Land, M. F., & McLeod, P. (2000). From eye movements to actions: How batsmen hit the ball. *Nature Neuroscience*, 3, 1340–1345.
- Lefton, L. A., Nagle, R. J., Johnson, G., & Fisher, D. E. (1979). Eye movement dynamics of good and poor readers: Then and now. *Journal of Reading Behavior*, 11, 319–328.
- Liu, A. (1998). What the driver's eye tells the car's brain. In G. J. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 431–452). Oxford, England: Elsevier.
- Loftus, G. R. (1983). Eye fixations on scenes and text. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 359–376). New York: Academic Press.
- Loftus, G. R., & Mackworth, N. H. (1978). Cognitive determinants of fixation location during picture viewing. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 565–572.
- Mertens, I., Siegmund, H., & Gruesser, O. J. (1993). Gaze motor asymmetries in the perception of faces during a memory task. *Neuropsychologia*, 31, 989–998.
- Nigg, J. T., Butler, K. M., Huang-Pollock, C. L., & Henderson, J. M. (2002). Inhibitory processes in adults with persistent childhood onset ADHD. *Journal of Consulting and Clinical Psychology*, 70, 153–157.
- Nodine, C. F., Carmondy, D. P., & Kundel, H. L. (1978). Searching for Nina. In Senders, J. W., Fisher, D. F., & Amdmonty, R. A. (Eds.), *Eye movements and the higher psychological functions*. (pp. 241–258). Wiley: New York.
- Olson, R. K., Kliegl, R., & Davidson, B. J. (1983). Dyslexic and normal children's tracking eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 816–825.
- Parker, R. E. (1978). Picture processing during recognition. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 284–293.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372–422.
- Rayner, K., & Pollatsek, A. (1992). Eye movements and scene perception. *Canadian Journal of Psychology*, 46, 342–376.



- Saida, S., & Ikeda, M. (1979). Useful visual field size for pattern perception. *Perception & Psychophysics*, *25*, 119–125.
- Tinker, M. A. (1946). The study of eye movements in reading. *Psychological Bulletin*, *43*, 93–120.
- van Diepen, P. M. J., & De Graef, P. (1994). *Line-drawing library and software toolbox* (Psychology Rep. No. 165). Leuven, Belgium: University of Leuven, Laboratory of Experimental Psychology.
- Vitu, F., O'Regan, J. K., & Inhoff, A. W. (1995). Mindless reading: Eye movement characteristics are similar in scanning letter strings and reading text. *Perception & Psychophysics*, *57*, 352–364.
- Walker-Smith, G. J., Gale, A. G., & Findlay, J. M. (1977). Eye movement strategies involved in face perception. *Perception*, *6*, 313–326.
- White, J. M., & Bedell, H. E. (1990). The oculomotor reference in humans with bilateral macular disease. *Investigative Ophthalmology and Visual Sciences*, *31*, 1149–1161.
- Whittaker, S. G., Budd, J., & Cummings, R. W. (1988). Eccentric fixation with macular scotoma. *Investigative Ophthalmology and Visual Sciences*, *29*, 268–278.
- Whittaker, S. G., Cummings, R. W., & Sweison, L. R. (1991). Saccade control with the fovea. *Vision Research*, *31*, 2209–2218.
- Yarbus, A. L. (1967). *Eye movements and vision*. New York: Plenum Press.

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