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Eye movements during information processing tasks: Individual differences and cultural effects

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Abstract

The eye movements of native English speakers, native Chinese speakers, and bilingual Chinese/English speakers who were either born in China (and moved to the US at an early age) or in the US were recorded during six tasks: (1) reading, (2) face processing, (3) scene perception, (4) visual search, (5) counting Chinese characters in a passage of text, and (6) visual search for Chinese characters. Across the different groups, there was a strong tendency for consistency in eye movement behavior; if fixation durations of a given viewer were long on one task, they tended to be long on other tasks (and the same tended to be true for saccade size). Some tasks, notably reading, did not conform to this pattern. Furthermore, experience with a given writing system had a large impact on fixation durations and saccade lengths. With respect to cultural differences, there was little evidence that Chinese participants spent more time looking at the background information (and, conversely less time looking at the foreground information) than the American participants. Also, Chinese participants' fixations were more numerous and of shorter duration than those of their American counterparts while viewing faces and scenes, and counting Chinese characters in text.

Keywords: Eye movements; Information processing; Reading; Scene perception; Visual search; Cultural effects

1. Introduction

Eye movements have been widely used to study a number of information processing tasks such as reading, scene perception, and visual search (Findlay & Gilchrist, 2003; Henderson, 2003; Liversedge & Findlay, 2000; Rayner, 1978; Rayner, 1998; Sereno & Rayner, 2003; Starr & Rayner, 2001). How long viewers look at a particular word or part of a scene and where they move their eyes have been used as key components in the development of models of eye movement control in reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; Pollatsek, Reichle, & Rayner, 2006; Rayner, Li, & Pollatsek, in press; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003), scene perception (Parkhurst, Law, & Niebur, 2002; Torralba, Oliva, Castelhano, & Henderson, 2006), and visual search (Findlay & Walker, 1999; Najemnik & Geisler, 2005). However, there are few data on how stable eye movement indices are across different tasks. If a given viewers' fixation durations and saccade lengths are long in one task, are they long in other tasks as well?

Andrews and Coppola (1999) reported the only study addressing this issue to date. Eye movements of 15 viewers were examined in five different stimulus environments: (1) darkness, (2) viewing simple textured patterns (different combinations of dots, squares, and lines), (3) scene perception, (4) visual search, and (5) reading. In the darkness condition, viewers were placed in a light-tight room and instructed to keep their eyes open with their gaze straight ahead. Five photographs of picturesque scenes were used for the scene viewing task and five pages from the children's book *The Great Waldo Search* were used in the search task (where

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viewers had to locate Waldo). The reading materials were taken from a number of sources.

Andrews and Coppola analyzed their data via correlational and principal components analyses and concluded that although the visual environment had a significant effect on eye movements, idiosyncracies were also evident. For example, fixation duration and saccade size for scene viewing correlated with those same parameters in the absence of visual stimulation and when looking at visual patterns. On the other hand, eye movement parameters during reading and visual search correlated with one another, but did not correlate with scene viewing, viewing simple patterns, or in the dark. However, there are potential problems with the study. First, a small number of stimuli were used in the scene perception, search, and simple pattern tasks, and these stimuli were used over and over again. Thus, viewers may have been overly familiar with each stimulus pattern and this could easily affect their eye movements. Second, in the reading situation, the letters were unusually large.[1] Finally, although a considerable amount of data was obtained from each participant, the number of participants was very small given that correlational and principal component analyses were utilized. In the present study, we used more participants and more stimuli, as well as more information processing tasks, in an attempt to provide a more complete answer to the issue of how stable eye movements are across different tasks.

In addition to examining the stability of eye movements across different tasks, we also examined the influence of culture on eye movements across the different tasks. Recently, Chua, Boland, and Nisbett (2005) reported that native Chinese and native English speaking participants had different eye movement patterns when looking at scenes. Specifically, they found that the Americans looked at the foreground objects in their study sooner and longer than the Chinese, and the Chinese were more likely to look at the background information in a scene. This finding, and other research (see Chua et al. for further discussion), lead them to suggest that Chinese and Americans view the world from quite different perspectives. They argued that cultural differences related to one's role in society (e.g., in the Chinese culture the individual is generally not as salient as in the case of American culture) were a causal factor in such an effect, and that culture can affect something as basic as how people look at scenes and how eye movements are controlled. Given this interesting finding, we compared the eye movements of native English speakers with no knowledge of Chinese to those of Chinese speakers with differing levels of knowledge of English. Their eye movements were recorded as they (1) read English sentences, (2) examined faces in anticipation of a memory test, (3) examined scenes in anticipation of a memory test, (4) searched for a target in a standard visual search task, (5) counted the number of times a Chinese character occurred in a passage of text, or (6) searched for a Chinese character. In addition, all participants with knowledge of Chinese read Chinese sentences. It should be noted that we used more tasks than Andrews and Coppola used in an attempt to obtain more reliable data. Furthermore, the tasks used are highly representative of those used in many eye movement studies (Rayner, 1998).

[1] The article indicates that the letters were 4 deg wide and 4 deg tall. However, this was apparently a misprint and the letters were 1 deg wide and 1 deg tall (Tim Andrews, personal communication, August 30, 2006), which is still fairly large.

2. Methods

2.1. Participants

Seventy-four participants were recruited at the University of Massachusetts at Amherst. They received course credit or they were paid for their participation. They all had normal uncorrected vision or their vision was corrected via contact lenses or glasses.

The participants were divided into three different groups (depending on their knowledge and fluency with Chinese and English). The *native English* speaking group (referred to as the *American* group) consisted of 24 participants; they attended school in the United States (US), and learned to read English in elementary school, but had no knowledge of Chinese. The *native Chinese* group consisted of 23 native speaking Chinese participants who attended school in China; they started to learn to read Chinese in elementary school, started to study English in middle school in China, and were also fairly fluent in English. Though they could read Chinese and English, because they came to the US after their college education, we call them native Chinese to distinguish them from a third group. The *Bilingual* group[2] consisted of 27 participants. Thirteen of them had Chinese parents, but they were born in the US or moved to the US before the age of 5, and they attended school (and learned to read English) in the US. Seven other participants were Chinese who initially learned to read Chinese in elementary school in China, but they moved to the US to attend school before the age of 14. Finally, seven participants in this group were the same as native English readers except they learned to read and speak Chinese in college. Overall, the participants in the study differ in terms of their ability to read English and Chinese, and also in terms of their cultural background.

2.2. Apparatus

Eye movements were monitored using an EyeLink II tracker sampling pupil and corneal reflections at 250 Hz. Participants viewed stimuli using both eyes, but only the right eye was monitored. Stimuli were presented on a 19 in. LCD monitor controlled by a Dell PC with a display resolution of 1024×768 pixels. Participants responded by pressing a button on a button box. Although the eyetracking system compensates for head movements, a chin-rest located 60 cm away from the monitor was used to minimize head movements.

2.3. Tasks and procedures

All participants performed the following six tasks: (1) English reading, (2) face processing, (3) scene perception, (4) visual search, (5) Chinese character count, and (6) Chinese character search. In the English reading task, 40 English sentences (which we generated) were read (in Times New Roman font 20 with letters subtending .45 deg). The average sentence length was 12 words, with a range from 9 to 16 words. All sentences fit

[2] The descriptor "bilingual" is used for this group purely as a matter of convenience. Clearly, all of the participants in the native Chinese group are bilingual (in that they can read and speak both Chinese and English). Indeed, they are more fluent bilinguals than those in the group we have labeled "bilingual". The latter group does not speak or read Chinese nearly as well as they speak and read English.

onto a single line on the display. Participants read each sentence and then pressed a button that resulted in either the next sentence or a comprehension question (which appeared following 10 randomly chosen sentences).

In the face processing and scene perception tasks, participants were shown 16 pictures of female faces (from Henderson, Williams, & Falk, 2005) and 24 pictures of scenes and asked to remember them for a later memory test; the faces and scenes were presented for 10 s. The faces were roughly 18 deg wide and 27 deg high. The scenes were color photographs of real-world scenes: 20 images contained separable points of interest (typically people) while four others were indoor images of rooms with no specific point of interest. The scenes were taken from a photographic collection (Lockwood, 2000) and were scanned and cropped so that they were 800×600 pixels in size; the entire picture subtended roughly 36 deg (wide) by 29 deg (high). Participants were asked to examine the scenes and faces in anticipation of a recognition memory task at the end of the experiment.[3]

In the visual search task, participants were asked to find a brown square that was part of an array of brown circles and pink squares. Each item in the array subtended 2.4 deg. Each array had 7, 13, or 19 items, and the brown square target was present on half the trials. The location of each item in a search array was chosen with a procedure that was designed to keep the density of elements constant across trials. In this procedure, the location of a given item was first selected randomly, and the location of each distractor item was then chosen so that its edge was no further than 25.2 mm from the closest of the existing items, and not closer than 20.0 mm from any of the existing items. Because the first location was selected randomly, the items appeared in a "clump" that could be anywhere within the display. Thus, density and eccentricity did not vary systematically across set sizes. There were 90 experimental trials preceded by 10 practice trials.

In the Chinese character count task, participants counted the occurrences of a Chinese character in a paragraph of Chinese text. There were six paragraphs, with 130–160 characters in each paragraph. Three of them were meaningful paragraphs taken from a Chinese magazine; the other three were the same characters as the other paragraphs, but the order of characters was randomly mixed so that they did not make any sense. There were two or three instances of the target character across the different paragraphs. In the Chinese search task, participants searched for a specific character in a randomly arranged array of Chinese characters. The target was present in half of the trials. There were 10 practice trials and 40 experimental trials. The set size was 8, 16, or 32 and the character was presented randomly in the display.

Those participants who could read Chinese read 36 Chinese sentences (taken from Rayner, Li, Juhasz, & Yan, 2005). The Chinese characters were .9 deg wide and high. The length of these sentences averaged 20 characters, and ranged from 14 to 39 characters. The sentences were presented on a single line on the display. Comprehension questions appeared following a randomly selected nine sentences. All of the tasks were preceded by detailed instruction in English and some practice trials. Half of the participants did the tasks in the order described above, the others in the reverse order.

3. Results

We used fixation duration and saccade size as primary indices of temporal and spatial processing in the tasks. It is generally assumed (see Rayner, 1998) that (1) fixation duration reflects the time needed to process the information around fixation and the time needed to plan the next saccade and (2) saccade size is related to how much information can be processed on a fixation and how the next saccade target is selected. Fixations more than three standard deviations above the mean for each individual participant were not analyzed.

3.1. Eye movement measures for the different tasks

Fixation durations and saccade sizes varied across the tasks (see Table 1). The average fixation durations and saccade sizes in the different tasks were quite consistent with prior reports (see Rayner, 1998 for an overview). For all participant groups, the visual search and Chinese character search tasks yielded shorter fixation durations (210 and 199 ms, respectively) and longer saccades (5.66 and 7.1 deg) than the other tasks. The reading tasks yielded medium sized fixation durations (254 ms for English and 277 ms for Chinese) and the smallest saccade sizes (2.4 deg for English and 2.6 deg for Chinese[4]). The Chinese count task yielded fixation durations (263 ms) that were similar to reading, but saccade size was somewhat larger (3.75 deg). Face processing and scene perception yielded fairly long fixations (291 and 280 ms, respectively) and large saccades (3.86 and 5.26 deg) for all participant groups, although for the bilingual group, the fixation durations in the Chinese reading task were even longer (330 ms, along with smaller saccades, 1.84 deg). Most participants in this group acknowledged that their understanding of Chinese speech (which was generally good) exceeded their ability to read Chinese. Their long fixation durations and short saccade sizes are consistent with this fact.

To test these eye movement differences, analyses of variance (ANOVA) were carried out on the fixation duration and saccade size data.

3.1.1. Fixation duration

The fixation duration data for the tasks other than Chinese reading were submitted to an ANOVA with task as a within participant factor and group as a between participant factor. The ANOVA yielded a significant main effect of task, $F(5,355) = 163.59$, $p < .001$, and a marginally significant main effect of group, $F(2,71) = 2.60$, $p < .10$. The interaction between task and participant group was also significant, $F(10,355) = 5.51$, $p < .001$. An ANOVA for each participant group showed an effect of task: Chinese

[3] Participants received two faces and two scenes in a recognition memory test. In each case, they saw one old and one new stimulus. Most of the participants were correct in accurately recognizing old and new stimuli.

[4] The saccade sizes in Table 1 are for all saccades and include both forward saccades and regressions. All saccades were used in the data analysis for comparability across tasks. However, the inclusion of all saccades yielded mean values that resulted in opposite going trends for Americans versus Chinese. Specifically, since a high proportion of the regressions of the American's were quite short, the mean saccade length in Table 1 when translated into character spaces is 5.1 spaces. Conversely, regressions made by the Chinese tended to be much larger, and the mean saccade length in Table 1 when translated into character spaces is 3.6 characters. When only forward going saccades were computed, the average saccade length for the Americans when reading English was 7.5 letter spaces and for the Chinese when reading Chinese was 2.5 character spaces.

Table 1
Means (and standard errors) for fixation duration (ms) and saccade size (degrees) for the different groups of participants

Group	English reading	Face processing	Scene perception	Visual search	Chinese count	Chinese search	Chinese reading
Fixation duration							
Chinese ($n = 23$)	268 (9.26)	275 (8.00)	264 (6.58)	206 (4.29)	238 (5.78)	193 (3.12)	230 (5.48)
American ($n = 24$)	247 (5.68)	296 (9.79)	289 (8.97)	209 (5.17)	277 (5.16)	204 (4.24)	—
Bilingual ($n = 27$)	246 (5.62)	301 (9.55)	288 (6.27)	215 (4.98)	275 (6.29)	200 (3.22)	330 (10.13)
Total ($n = 74$)	254 (4.10)	291 (5.42)	280 (4.38)	210 (2.81)	263 (3.90)	199 (2.09)	277 (7.42)
Saccade size							
Chinese ($n = 23$)	2.19 (0.09)	3.73 (0.12)	5.21 (0.12)	5.45 (0.11)	4.29 (0.23)	7.41 (0.23)	3.26 (0.15)
American ($n = 24$)	2.31 (0.11)	3.96 (0.10)	5.18 (0.14)	5.64 (0.11)	2.97 (0.15)	6.38 (.27)	—
Bilingual ($n = 27$)	2.65 (0.09)	3.89 (0.13)	5.38 (0.18)	5.87 (0.11)	3.97 (0.24)	7.47 (0.21)	1.84 (0.11)
Total ($n = 74$)	2.40 (0.06)	3.86 (0.07)	5.26 (0.09)	5.66 (0.07)	3.75 (0.14)	7.10 (0.15)	2.60 (0.11)

[$F(5,110) = 52.69$, $p < .001$], American [$F(5,115) = 67.96$, $p < .001$], and Bilingual [$F(5,130) = 58.33$, $p < .001$]. For the Chinese group, fixation durations tended to group according to different tasks. Specifically, fixation durations were similar for English reading (268 ms), face processing (275 ms), and scene perception (264 ms), and much shorter for visual search (206 ms) and Chinese search (193 ms). Fixation durations in the Chinese count task (238 ms) and Chinese reading (230) were similar and intermediate between the other two task categories. In contrast, for both the American and Bilingual groups, fixation durations were longer for face processing (296 and 301 ms) and scene perception (289 and 288 ms) than for English reading (247 and 246 ms). A contrast that tested the difference between fixation duration in English reading and the average durations in the face processing and scene perception tasks was significant for both the American group, $t(23) = 5.08$, $p < .001$, and the Bilingual group, $t(26) = 5.37$, $p < .001$. Comparisons across groups showed that the magnitude of this difference was greater for the American group than the Chinese group, $t(45) = 3.71$, $p < .001$, and also greater for the Bilingual group than the Chinese group, $t(48) = 3.89$, $p < .01$.

For the visual search task and the Chinese search task, there were no significant differences across the three groups (ts < 1). In contrast, the Chinese group had shorter fixation durations in the Chinese count task (238 ms) than either the Americans (277 ms), $t(45) = 5.01$, $p < .001$, or the Bilinguals (275 ms), $t(48) = 4.26$, $p < .001$. Fixation durations were much shorter for the Chinese group (230 ms) when reading Chinese than for the Bilingual group (330 ms) when reading Chinese, $t(41) = 8.04$, $p < .001$, which is further evidence that the Bilingual group was not as facile with Chinese as were the native Chinese. Finally, the Chinese groups' fixations were shorter when reading Chinese (230 ms) than when reading English (268 ms), $t(22) = 5.71$, $p < .001$.

3.1.2. Saccade size

The same set of ANOVAs was carried out for saccade size. There was a main effect of task, $F(5,355) = 434.50$, $p < .001$, and an interaction between task and group, $F(10,355) = 6.53$, $p < .001$. There was also a main effect of task for the Chinese, $F(5,110) = 134.59$, $p < .001$, American, $F(5,115) = 153.59$, $p < .001$, and Bilingual groups, $F(5,130) = 163.78$, $p < .001$.

In contrast to the fixation duration data, which showed some clear differences due to task and culture, there were fewer such differences in the saccade length data. There were obvious differences in saccade size due to task, with English reading yielding the shortest saccades (2.4 deg) and the Chinese search task yielding the longest saccades (7.1 deg). Scene perception and visual search both yielded average saccade sizes that were on the order of 5.5 deg, and the face processing and Chinese count tasks yielded average saccade sizes that were on the order of 3.8 deg. Across the three participant groups, saccade size tended to be quite similar for most of the tasks, with the main differences involving those where knowledge of Chinese led to longer saccades. Specifically, saccade size in the Chinese character count task (2.97 deg) and the Chinese character search task (6.38 deg) was reliably smaller for the Americans than for the Chinese and Bilinguals, ts all >2.92, $p < .01$. Finally, consistent with the view that the Bilinguals were not as skilled in reading Chinese, they made smaller saccades (1.84 deg) than did the Chinese (3.26 deg) while reading Chinese, $t(41) = 6.92$, $p < .001$.

3.2. Individual differences: Analyses of correlations

Correlations were calculated to examine individual differences in the eye movement measures. For example, a strong positive correlation between two tasks for fixation duration indicates that participants with longer fixation durations in one task also tend to have longer fixation durations in the other. Because correlations calculated over the entire group of participants could be distorted by differences in the means for the three groups, we calculated correlations separately for each group. There were a large number of correlations, 15 for the American participants and 21 each for the Chinese and Bilingual groups who had the additional task of Chinese reading.

3.2.1. Fixation durations

The correlations (broken down by group) among the different tasks for fixation duration are presented in

Table 2
Correlation coefficients for fixation duration among the different tasks for Chinese, Americans, and Bilinguals

	English reading	Face processing	Scene perception	Visual search	Chinese count	Chinese search	Chinese reading
(a) Chinese (n = 23)							
English reading							
Face processing	.58**						
Scene perception	.59**	.91**					
Visual search	.34	.48*	.44*				
Chinese count	.68**	.40	.54**	−.09			
Chinese search	.61**	.53**	.57**	.40	.47*		
Chinese reading	.72**	.22	.19	.28	.47*	.31	
(b) American (n = 24)							
English reading	—						
Face processing	.44*	—					
Scene perception	.16	.84**	—				
Visual search	.33	.63**	.64**	—			
Chinese count	.33	.64**	.62**	.50*	—		
Chinese search	.57**	.58**	.45*	.66**	.41*	—	
Chinese reading							
(c) Bilingual (n = 27)							
English reading	—						
Face processing	.00	—					
Scene perception	.15	.78**	—				
Visual search	.33	.33	.20	—			
Chinese count	−.14	.47*	.42*	.06	—		
Chinese search	.19	.43*	.52**	.50**	.29	—	
Chinese reading	−.34	.23	−.18	.13	.21	−.04	—

* $p < .05$.
** $p < .01$.

Table 2. Although confidence intervals are large for correlations based on 23–27 participants, there seem to be some systematic differences among the groups. Perhaps the most interesting differences concern the correlations with the reading tasks. For the Bilingual group, neither Chinese nor English reading came close to correlating significantly with any other task. In contrast, for the Chinese group, English and Chinese reading correlated strongly, $r = .72$, and English reading correlated with all other tasks except visual search. Participants in the American group, of course, had no Chinese reading task; for them, English reading had significant correlations with Chinese character search and face processing. For the non-reading tasks, all but one of the 30 correlations for the three groups was positive and most of them were significant (10/10 for the Americans, 7/10 for the Chinese, and 6/10 for the Bilinguals). It is interesting to note that the correlation between English reading and visual search did not reach significance for any of the groups. However, the correlations were remarkably stable across the three groups (either .33 or .34).

Given the fairly large correlation matrix, we further explored the task structure by performing principal components analyses (with varimax rotations) for each of the three groups. In doing so, we did not include the data from the Chinese reading task because we wished to compare the factor structures across the three participant groups. In each case, the analysis produced two primary factors that between them accounted for most of the variance in the scores −78.8% for the Chinese group, 77.6% for American group, and 67.7% for the Bilingual group. As can be seen in Table 3, the factor structure was very similar for the American and Bilingual groups. If we consider a factor loading of .40 as the cutoff, for the American group, all tasks except English reading loaded on the first factor, and English reading, visual search, and Chinese search loaded on the second factor. For the Bilingual group, the structure was the same except that visual search no longer loaded on the first factor and loaded more heavily on the second. The structure for the Chinese group was somewhat different: English reading loaded heavily on the first factor along with all other tasks except visual search. Visual search loaded heavily on the second factor along with face processing, scene perception, and Chinese search. The two-factor solutions accounted for the variability in the task data quite well. The communalities (i.e., the proportions of variability accounted for by the two factors) exceeded .60 for each task in each of the three groups.

We then used the LISREL 8 software package (Jöreskog & Sörbom, 1993) to conduct confirmatory factor analyses.[5] We hypothesized the factor structure described above for the American group, in which all measures except English

[5] Given that the sample sizes are very small for this type of multivariate analysis, the results should be interpreted with extreme caution.

Table 3
Factor loadings and communalities (h^2) for the principal components analysis with varimax rotation for fixation durations

Task	Chinese			American			Bilingual		
	F1	F2	h^2	F1	F2	h^2	F1	F2	h^2
English reading	.81	.31	.75	.09	.92	.86	−.15	.78	.63
Face processing	.56	.69	.79	.85	.34	.84	.87	.16	.78
Scene perception	.67	.61	.82	.95	.04	.90	.84	.22	.75
Visual search	−.04	.92	.85	.72	.40	.68	.23	.78	.66
Chinese count	.94	−.14	.90	.76	.21	.62	.75	−.21	.61
Chinese search	.62	.47	.61	.45	.76	.78	.57	.55	.63
Percent of variance accounted for	44.8	33.9		48.4	29.2		40.4	27.3	

reading loaded on the first factor and English reading, visual search, and Chinese search loaded on the second factor, and allowed the factors to be correlated. The model was not rejected for the American group, $\chi^2(6) = 8.17$, $p = .226$, nor for the Bilingual group, $\chi^2(6) = 7.28$, $p = .296$, but was strongly rejected for the Chinese group, $\chi^2(6) = 22.05$, $p = .001$.

3.2.2. Saccade size

Fewer correlations for saccade length (see Table 4) were significant than for fixation duration. Again for the Chinese group, Chinese reading correlated only with English reading. However, English reading did not correlate with any of the non-reading tasks. For the Bilingual group, as with fixation duration, Chinese reading did not correlate with any other task. However, for this group, English reading had positive correlations with all of the non-reading tasks, including significant correlations with scene perception and Chinese count. For the American group, English reading correlated positively with all other tasks, although only the correlations with visual search and Chinese search were significant. For the non-reading tasks, only two saccade length correlations were significant for the Chinese group: scene perception with face processing and Chinese search with Chinese count. For the American group, 5 of the 10 correlations were significant: scene perception with face processing, visual search, and Chinese search; and visual search with face processing and Chinese search. Finally, four correlations were significant for the Bilingual group: scene perception with face processing, Chinese count, and Chinese search; and Chinese search with Chinese count.

Again, we performed principal components analyses using the correlation matrices for the Chinese, American,

Table 4
Correlation coefficients for saccade size among the different tasks for Chinese, Americans, and Bilinguals

	English reading	Face processing	Scene perception	Visual search	Chinese count	Chinese search	Chinese reading
(a) Chinese (n = 23)							
English reading	—						
Face processing	.02	—					
Scene perception	.14	.52*	—				
Visual search	−.03	.34	−.14	—			
Chinese count	−.032	−.05	.04	.07	—		
Chinese search	.04	−.10	−.15	.03	.57**	—	
Chinese reading	.66**	.35	.34	.12	.32	.14	—
(b) American (n = 24)							
English reading	—						
Face processing	.39	—					
Scene perception	.28	.73**	—				
Visual search	.44*	.44*	.50*	—			
Chinese count	.22	.18	.25	.34	—		
Chinese search	.78**	.39	.46*	.43*	.20	—	
Chinese reading							
(c) Bilingual (n = 27)							
English reading	—						
Face processing	.23	—					
Scene perception	.60**	.60**	—				
Visual search	.26	.34	.29	—			
Chinese count	.44*	.07	.50**	.34	—		
Chinese search	.42	.16	.56**	.28	.55**	—	
Chinese reading	−.21	−.15	−.12	.22	.08	.32	—

* $p < .05$.
** $p < .01$.

Table 5
Factor loadings and communalities (h^2) for the principal components analysis with varimax rotation for saccade lengths

Task	Chinese				American			Bilingual		
	F1	F2	F3	h^2	F1	F2	h^2	F1	F2	h^2
English reading	.26	.08	.49	.31	.19	.93	.90	.67	.32	.55
Face processing	.87	−.06	−.30	.85	.85	.17	.75	−.04	.95	.90
Scene perception	.83	−.04	.36	.82	.90	.14	.83	.60	.66	.80
Visual search	.24	.18	−.85	.81	.63	.40	.56	.30	.52	.36
Chinese count	.04	.88	−.01	.78	.41	.19	.20	.86	−.05	.74
Chinese search	−.12	.88	.01	.90	.29	.88	.86	.81	.15	.68
Percent of variance accounted for	26.4	26.2	19.6		36.8	31.2		37.9	29.0	

Table 6
Correlation coefficients for fixation duration and saccade length across the different tasks for Chinese, Americans, and Bilinguals

	Chinese	American	Bilingual
English reading	−.32	−.12	−.06
Face processing	−.11	−.05	−.28
Scene perception	.20	.14	−.03
Visual search	−.11	−.06	.24
Chinese count	−.06	.07	−.21
Chinese search	.01	−.40	−.01
Chinese reading	−.06	—	.28

and Bilingual groups (see Table 5). Two main factors were obtained for the American and Bilingual groups, but for the Chinese group, because of the many low correlations among tasks, a three-factor solution was necessary.

The principal components analyses were less successful in accounting for the saccade length data than they had been for fixation duration. The proportions of variability accounted for by the factors were less, even though they now included a third factor for the Chinese group. Moreover, the three factors obtained for the Chinese group did not account for the English reading task well ($h^2 = .31$). Communalities were also low for the Chinese count task in the American group and for visual search in the Bilingual group. Nonetheless, the factor structure for the American group was very similar to that obtained using the fixation duration data with all measures except English reading loading on one factor, and English reading, visual search, and Chinese search loading on a second factor.

We again performed confirmatory factor analyses using the factor structure described for the fixation duration data. The model was consistent with the saccade length data for the American group, $\chi^2(6) = 4.68$, $p = .585$. However, it was not at all consistent with the saccade length data for the Chinese and Bilingual groups.[6]

3.2.3. Correlation between fixation duration and saccade length

The correlation between fixation duration and saccade length was computed for each participant in each task. Table 6 shows the average correlations across the different tasks for each of the three participant groups. With the exception of the Americans in the Chinese search task (where the correlation was marginally significant, $p = .055$), none of the other correlations approached significance (all $p > .15$). These results are consistent with results reported by Rayner and McConkie (1976) for reading and Castelhano and Henderson (in press) for scene perception. The present results, as well as those reported previously by Rayner and McConkie and by Castelhano and Henderson, suggest that the mechanisms involved in deciding when to move the eyes are different from (or somewhat independent of) those involved in deciding where to look next.

3.3. The influence of language experience on reading

In order to examine the influence of language experience on reading, participants were categorized into three groups according to their experience with written English. Group E1 ($n = 44$) consisted of all participants educated in the US. Group E2 ($n = 7$) consisted of Chinese who started to read English in middle school in China, but then came to the US and studied English in middle or high school for at least 3 years. Group E3 ($n = 23$) consisted of Chinese participants who started to read English in middle school in China but did not come to the US until they started graduate school.

Participants who could read Chinese were divided into three groups based on their experience with written Chinese. Group C1 ($n = 29$) consisted of native Chinese speakers who attended elementary school in China. Group C2 ($n = 7$) were English speakers who started to study Chinese in middle or high school in the US. Group C3 ($n = 13$) consisted of native English speakers who first started to study Chinese while attending college.

In the reading tasks, fixation duration decreased and saccade size increased with reading experience (see Fig. 1). This pattern was evident in both English and Chinese reading. For both tasks, we submitted the fixation duration and saccade length data to one-way ANOVAs with skill level as the factor, followed by trend analyses. For English reading, the ANOVA revealed a

[6] It was sufficiently inconsistent that the solution for the model did not converge and no test statistics were produced.

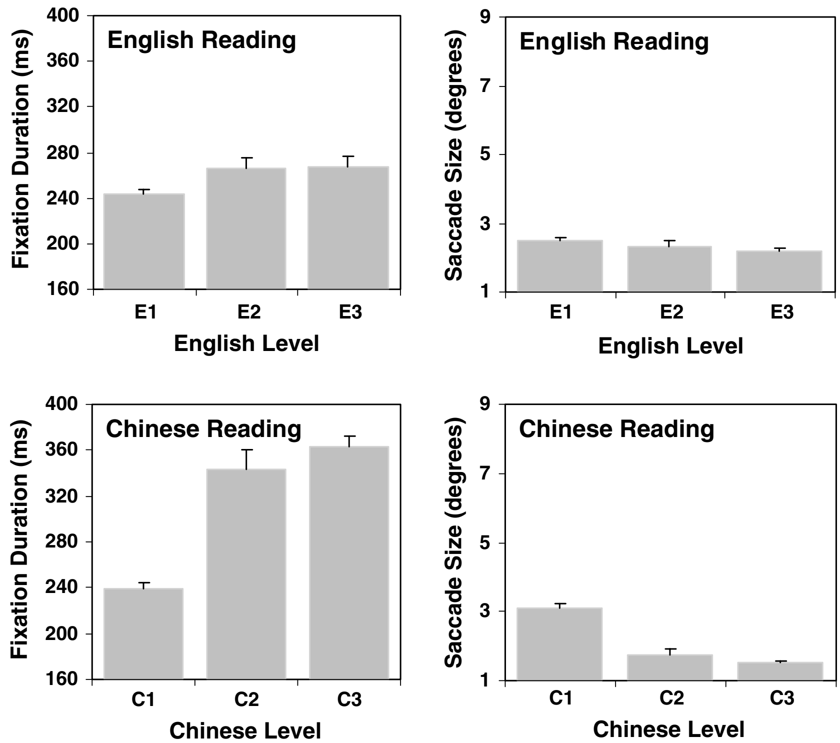

Fig. 1. Fixation duration and saccade size for reading tasks as a function of experience with written English and Chinese. The top left panel shows the average fixation duration for English reading; the top right panel shows the saccade size for English reading; the bottom left panel shows the fixation duration for Chinese reading; the bottom right panel shows the saccade size for Chinese reading. Error bars are standard errors.

significant effect of English skill level, $F(2,71) = 4.57$, $p < .05$, and a linear trend, $F(1,71) = 8.03$, $p < .01$, for fixation duration. There was also an effect of English skill level, $F(2,71) = 3.40$, $p < .05$, and a linear trend, $F(1,71) = 6.69$, $p < .05$, for saccade size. For Chinese reading, there was an effect of Chinese reading level, $F(2,40) = 59.02$, $p < .001$, and a linear trend, $F(1,40) = 96.02$, $p < .001$, for fixation duration. There was also an effect of Chinese reading level, $F(2,40) = 21.44$, $p < .001$, and a linear trend, $F(1,40) = 34.68$, $p < .001$, for saccade size.

3.4. How does knowledge about Chinese influence the eye movement patterns in the Chinese related tasks?

In the Chinese character count and Chinese character search tasks,[7] fixation duration decreased and saccade size increased with increasing knowledge of Chinese (see Fig. 2). In the Chinese count task, the ANOVA yielded an effect of Chinese reading level, $F(3,70) = 11.16$, $p < .001$, and there was a linear trend, $F(1,70) = 27.70$, $p < .001$, on fixation duration. There was also an effect of knowledge of Chinese, $F(3,70) = 6.04$, $p < .01$, and a linear trend, $F(1,70) = 11.03$, $p < .001$, on saccade size.

For the Chinese search task, we found a similar pattern. There was a marginally significant effect of Chinese reading level, $F(3,70) = 2.33$, $p < .10$, and a significant linear trend, $F(1,70) = 6.42$, $p < .05$, on fixation duration. There was also an effect of knowledge of Chinese, $F(3,70) = 3.96$, $p < .05$, and a linear trend, $F(1,70) = 10.06$, $p < .01$, on saccade size.

3.5. How does culture influence eye movements?

To further examine how culture influences eye movements, eye movements in the scene perception task were analyzed separately. We included three groups of participants in this analysis. Native Chinese speakers, native English speakers, and Chinese who were born in the US or came to the US by the age of 5 (American-born Chinese, $n = 13$). Fixation duration, saccade length, and the number of fixations were submitted to one-way ANOVAs. The effect of participant group was non-significant for saccade length ($F < 1$), but marginally significant for both fixation duration, $F(2,57) = 2.66$, $p < .10$, and the number of fixations, $F(2,57) = 2.85$, $p < .10$. Planned t-tests showed that the Chinese group had shorter fixations, $t(45) = 2.27$, $p < .05$, and more fixations, $t(45) = 2.09$, $p < .05$, than the American group

[7] In the analyses discussed in this section, data from the American group (no experience with Chinese) were also included in the ANOVA (and referred to as C4 in Fig. 2).

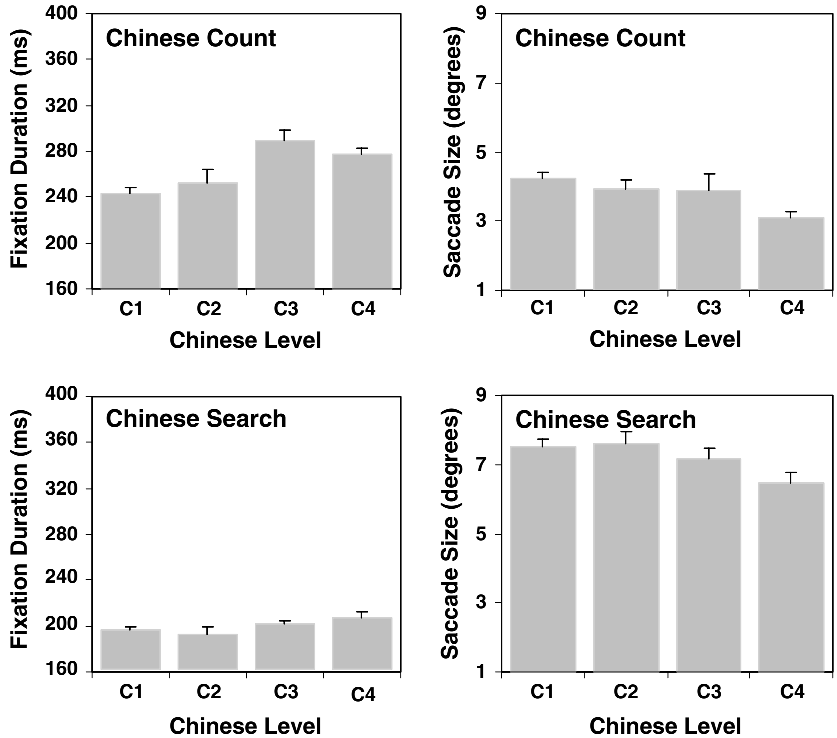

Fig. 2. Fixation duration and saccade size in the Chinese character count and Chinese character search tasks. Top panels are fixation duration (left) and saccade size (right) for the Chinese count task; bottom panels are fixation duration (left) and saccade size (right) for the Chinese search task. Error bars are standard errors.

(see Fig. 3).[8] The American-born Chinese group made fewer fixations than the Chinese, $t(34) = 2.17$, $p < .05$.

As per Chua et al. (2005), we examined the extent to which native Chinese participants were more likely to look at the background information and spend less time looking at important objects in the foreground of a scene in comparison to the Americans. To do so, we selected a number of scenes for which it was quite easy to discriminate the background from the foreground. The scenes used were both indoor and outdoor photographs that contained people or animals. We identified points of interest in the image and classified these points as foreground and the remainder as background. For example, one image was of three bears on a snowy mountain side. Each bear was selected as a foreground element, as was the mountain top, and the remaining portions of the scene (e.g., the sky and the ground) were identified as background. The number of foreground elements ranged from 1 to 6. A region that encompassed each of these elements was defined as the smallest rectangle that could contain the element and was used for all eye movement analyses.

We found no difference between the Chinese and Americans in the mean amount of time spent viewing the background information [$F < 1$]. In fact, the Chinese (2489 ms) spent less time viewing the background compared to the Americans (2565 ms). There was a tendency for the Chinese (6445 ms) to spend less time looking at the foreground elements than the Americans (6633 ms), but the effect was not significant ($p > .10$). Also, because Chua et al. reported differences in the amount of time devoted to the background and foreground elements over time, we did a time epoch analysis in which we examined the proportion of fixations devoted to the foreground elements and background elements for each ordinal fixation (up to the 16th fixation on the scene). In our analysis, we would expect a three-way interaction of object type, ordinal fixation, and culture. However, as is evident in Fig. 4, no such interaction was apparent ($F < 1$). Thus, we found no evidence for different eye movement patterns over time in looking at the scenes.

One way to reconcile the differences between our findings and those of Chua et al. (2005) is to examine the differences in the scenes used in the two studies. Chua et al. used scenes in which they could clearly identify a single foreground object. In fact, several of the stimuli were backgrounds with an object added to the scene via photo-editing. This technique allowed them to clearly define the location and number of objects present in a scene. Our

[8] It is interesting to note that in the face processing task, the Chinese made more fixations (27.2) than the American (25.7) and the Bilinguals (24.9), $t(72) = 2.27$, $p < .05$. Thus, in both the face processing task and the scene perception task, the Chinese had shorter fixation durations, but made more fixations than the American and Bilinguals. The other task in which the Chinese had markedly shorter fixations than the American and Bilingual groups was the Chinese character count task. Here, the Chinese actually made fewer fixations (132.5) than the American (160.1) or Bilinguals (154.1), $t(72) = 2.15$, $p < .05$.

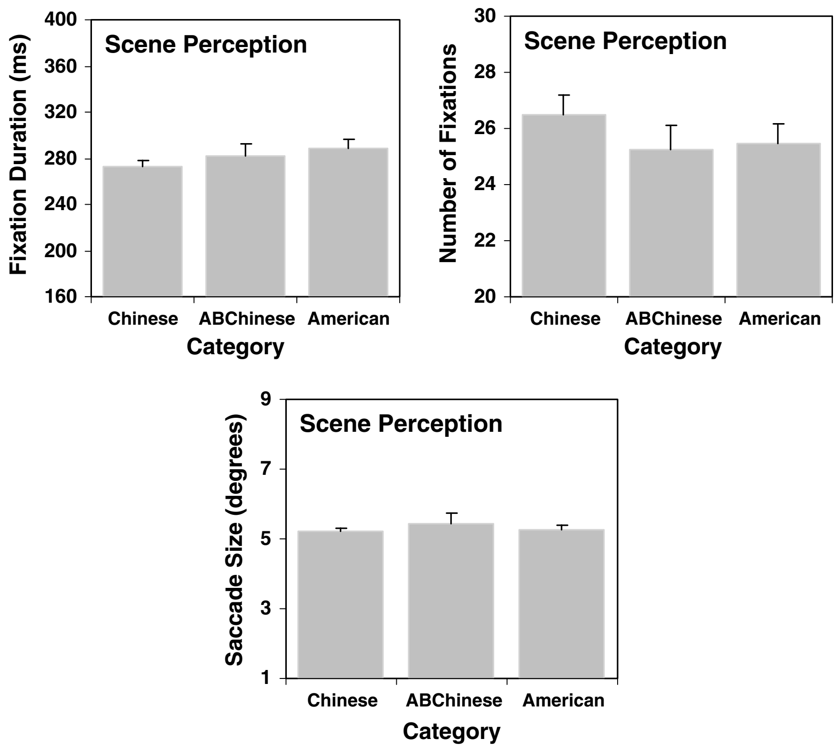

Fig. 3. Fixation duration (top left), number of fixations (top right), and saccade size (bottom) in the scene perception task for different participant groups: Chinese (Chinese who attended school in China and came to the US after their undergraduate education); Americans (Americans who attended school in the US); ABChinese (American-born Chinese or Chinese who came to the US before 5 years of age and attended school in the USA). Error bars are standard errors.

stimuli were photographs that were selected to have multiple points of interest, including people, and backgrounds were large areas of the scene with no objects of interest at all. The extent of the background in our scenes was also presumably much smaller than Chua et al., averaging 56.5% of the scene area. As a further test, we selected a subset of our stimuli (six scenes) with one or two well-defined points of interest that more closely emulated the stimuli of Chua et al. We analyzed both the total time and the fixation count for the Chinese and American groups on the foreground and background for these scenes. Although the interaction between participant group and scene areas

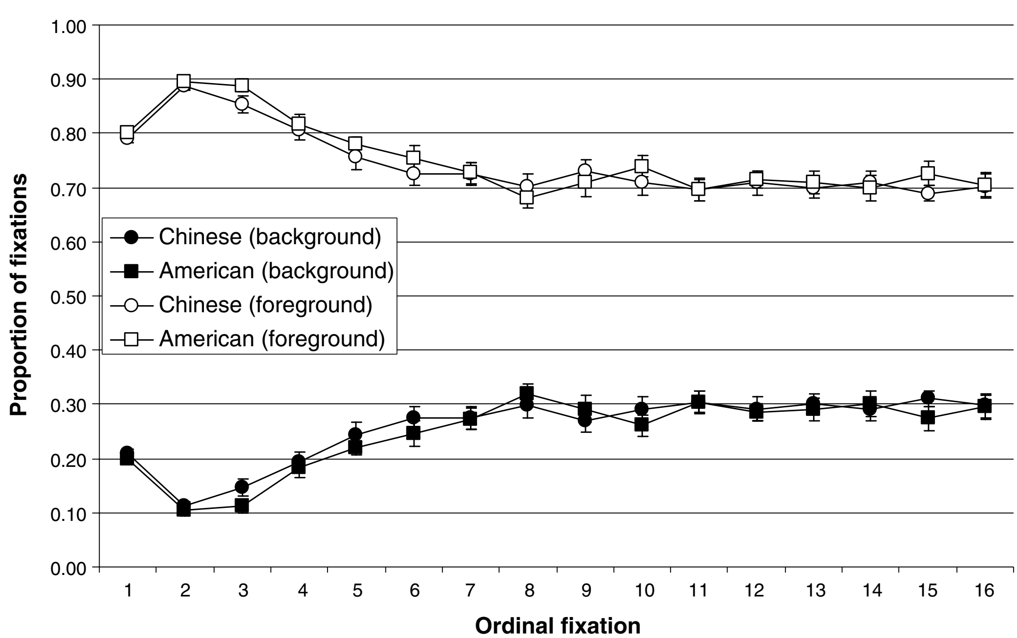

Fig. 4. Proportion of fixations on the background and foreground elements for the American and Chinese participants.

was not significant for either measure [total time: $F(1,45) = 2.259$, $p = .14$; fixation count: $F(1, 45) = 2.084$, $p = .16$], we compared the two groups for each scene area for each measure. There was no difference in the total time spent viewing the background of the scenes [Chinese: 4346 ms; English: 4183 ms, $t < 1$], but there was a difference in the total amount of time participants spent viewing the foreground elements, with the Chinese spending less time (4299 ms) on the defined point of interest than the Americans [4813 ms; $t(45) = 2.10$, $p = .04$]. The total time results appear similar to the average fixation duration data from Chua et al. In contrast to the total time, the two groups had similar number of fixations on the points of interest [Chinese: 13.1; English: 12.5; $t < 1$]. However, replicating the findings from Chua et al., the Chinese had significantly more fixations (16.3) on the background than the Americans [13.8; $t(45) = 2.34$, $p = .02$]. The results of this analysis of a subset of the scenes that are more similar to the Chua et al. stimuli replicate aspects of the previous data. These results may indicate that given a limited number of points of interest in a scene, the two groups may differ. However, when there are many more areas that might be of interest, the two groups appear to view the scenes in similar ways.

4. Discussion

The results of the present study suggest that fixation durations for a given individual tend to be fairly stable across different tasks. As we noted earlier, for the non-reading tasks, most of the correlations were positive and most of them were also significant. For the American and Bilingual groups, fixation durations in English reading did not correlate especially well with fixation durations in the other tasks, while for the Chinese group fixation durations in English reading did tend to correlate highly with the other tasks. It was quite striking that fixation durations in scene perception and face processing were highly correlated across all three participant groups. Recently, Castelhano and Henderson (in press) reported a correlation of .75 for fixation durations in scene perception and face processing (which is only a bit lower than the correlations we obtained). Castelhano and Henderson (in press) also reported high correlations in fixation durations (all above .93) when participants viewed line drawings, color photographs, and full color renderings of 3D models of scenes. Thus, when the task (scene perception) was constant, but the nature of the stimulus differed, very high correlations were obtained. With our stimuli, we also found that saccade length did not correlate as well across tasks as did fixation duration, but when the reading tasks were eliminated, the correlations tended to be positive (and many of them were significant).

Another interesting finding was that there was no significant correlation of fixation duration and saccade length within any of the tasks. As we noted earlier, Rayner and McConkie (1976) reported a similar result with reading and Castelhano and Henderson (in press) reported a similar result with scene perception. The present contribution is to demonstrate that the lack of correlation between fixation duration and saccade length extends across all of the tasks we examined. Thus, as noted by Rayner and McConkie and by Castelhano and Henderson, the mechanism responsible for determining when to move the eyes is largely independent of the mechanism responsible for determining where to move the eyes next. Certainly, within the context of reading, the prevailing view is that when to move the eyes is largely driven by cognitive processes while the decision about where to move is largely driven by low-level visually salient aspects of the stimulus.

Our results are generally consistent with prior research by Andrews and Coppola (1999), although they did not include as many tasks as we did nor did they have as many participants. Andrews and Coppola reported that principal components analyses of the correlational structure of their data suggested "...that one factor explains the majority of the variance between individuals for the dark, simple pattern, and natural scene conditions, whereas another factor explains the majority of the variance in the visual search and reading tasks (p. 2952)". Our principal components analyses suggest a similar structure for the American group, both for fixation duration and saccade duration data. In both cases, there was one factor loaded on by most of the tasks but *not* by English reading, and a second factor loaded on by English reading, and by both the visual search and Chinese search tasks. This factor structure was also consistent with the fixation duration data for the Bilingual group. It was not consistent with the saccade length data for the Bilingual group, nor was it consistent with the data from the Chinese group for either fixation duration or saccade length. Although these findings should be treated cautiously because we had small samples and because the results of factor analyses should be discussed in correlational, rather than causal language, they suggest that it is worth considering what processes the search tasks and reading may have in common. Whatever is going on, it seems fairly well established that there are systematic differences between the Chinese and American groups, with the Bilingual group falling somewhere in between.

In the remainder of this section, we will discuss first why there may be differences in eye movement characteristics between reading and the other tasks. We will not comment in detail on the finding that reading and visual search may share some similarities for eye movement characteristics. Perhaps participants often approach many visual search tasks via using a reading-like strategy in dealing with the visual array wherein they move their eyes from left-to-right (or right-to-left) and top-to-bottom across the array; thus, their eye movements might a bit more systematic in search than they might be in tasks like scene perception and face processing. However, this is purely speculation on our part. After discussing differences between reading and other tasks, we will then discuss issues related to cultural influences on eye movements.

For reading, it has been clearly demonstrated that lexical and other linguistic factors have a strong influence on fixation durations (see Rayner, 1998, for a review). Thus, longer fixations occur when difficult words are encountered and shorter fixations occur when words that are easy to process are encountered. To this extent the cognitive processes that directly influence fixation durations during reading are comparatively well understood, and the fact that these are specific to linguistic processing perhaps provides an indication as to why fixation durations in reading would not be highly correlated with other, non-linguistic, tasks. In contrast, the relationship between eye movements and the psychological processes underlying other visual tasks such as scene perception, visual search, and face perception are far less well understood. The fact that we obtained correlations in fixation durations for these different tasks does, however, suggest that there might indeed be aspects of processing that are common to them all. Perhaps in non-reading tasks, some kind of timing mechanism determines when the eyes move; such a common timing mechanism would be expected to lead to correlations across tasks, particularly in fixation durations (and to a lesser extend, saccade length). Another possibility is that something like visual saliency (Findlay & Walker, 1999) is the critical (and common) factor in determining when to move in the non-reading tasks.

Not surprisingly, the more experience participants had with either English or Chinese, the shorter the fixations and the longer the saccades. This result is more of an effect of experience than of culture. With respect to cultural effects, with our entire set of scene stimuli, we found little evidence consistent with the claims of Chua et al. that Chinese spend more time on the background information (and correspondingly less time on the foreground information) than Americans. However, when we restricted the analyses to a subset of our scenes presumably most like those used by Chua et al., we did find some evidence to suggest that the Chinese spent less time looking at the focal (foreground) objects. The results reported by Chua et al. are certainly intriguing, but they must be viewed with some caution given our results. Actually, our study is not a direct replication of Chua et al. in that they used a cut and paste procedure to put a prominent object in the foreground of most scenes. Thus, one might want to argue that their materials were better controlled than ours in terms of defining foreground and background. On the other hand, our scenes were all very natural[9] and it was rather easy to differentiate background from foreground. And, certainly one would expect that if the effect is robust that it should emerge in the scenes we used. Finally, while we have focused on differences in the scenes we used and Chua et al. used, it is also important to note that the instructions to participants varied across the experiments. Whereas we presented scenes to our participants with the expectation that they would have to remember them for a later test, Chua et al. asked their participants to make an aesthetic evaluation of the scene where they were asked to rate how much they liked the scene. It is also quite likely that task differences can in part account for the differences across the two studies.

Although we were unable to replicate Chua et al.'s main findings, we did find some cultural differences in eye movements in that our Chinese participants had systematically shorter fixations in the scene perception, face processing, and Chinese count tasks than the Americans. On the two search tasks, the fixation durations of the Chinese and Americans were very similar. Of course, the Americans had shorter fixations when reading English than did the Chinese, and the Chinese had shorter fixations when reading Chinese than English. The shorter fixation durations in the three tasks may provide evidence of a cultural effect. However, it is also important to note that the effect is due to the Chinese trading off number of fixations with fixation duration. In other words, while they made somewhat shorter fixations, they also made slightly more fixations (see Fig. 3). Here, it is important to note that Chua et al. found similar results. In their study, the Chinese participants had shorter fixation durations (on both the foreground object and the background) and more fixations (particularly on the background) than the Americans. An examination of the fixation dispersion in the scenes in the current study indicated that there was no difference between the Chinese and Americans in terms of how much of the scene was covered by a fixation. (In this analysis we divided each scene into a number of equal-sized regions and checked to see what the likelihood was that a fixation fell in any given region.) Given the consistency in our results and Chua et al.'s results, shorter fixation durations in the scene and face processing tasks coupled with more fixations might be evidence of a strategy effect that is reflective of a cultural difference between Chinese and Americans. The exact nature of this cultural difference is not fully clear at this point.

Finally, the Bilingual group was more variable overall in their eye movement behavior than the other two groups, but they clearly were more like the Americans than the Chinese (see Table 1). Even though their understanding and production of Chinese speech was reasonably good, their reading skill was not as good; they had some difficulty reading the Chinese sentences (their fixation durations were long and their saccade lengths were short) and their fixation durations in the Chinese count task were very similar to the Americans. However, most of them would argue that English was their first language (even though some of them initially learned to speak Chinese).

In summary, the present study yielded six important findings. First, there was generally intra-individual consistency in eye movement behavior across different tasks. If fixation durations were long for one person on one task, they tended to be long on other tasks; the same tended to be true for saccade size, though not as strongly. Second,

[9] In some of the scenes used by Chua et al. it is rather obvious that a cut-and-paste procedure was used so that they do not look fully natural. It is unclear to what extent this might influence their results.

however, eye movement behavior on some tasks did not correlate highly with other tasks. Specifically, eye movements in reading tended to not correlate particularly well with eye movements in the other tasks. Third, there was no correlation between fixation duration and saccade length in any of the tasks, suggesting that these two aspects of eye movements are under different control mechanisms. Fourth, experience with a particular writing system had a large impact on eye movements. Fifth, across all of the scenes in our sample, the Chinese group did not spend more time looking at the background information (and, conversely less time looking at the foreground) than the Americans; however, when we restricted the scenes to a subset that were most similar to the scenes used by Chua et al. there was some evidence that the Chinese spent more time looking at the background information. Sixth, Chinese fixation durations tended to be systematically shorter than those of Americans in the face perception, scene perception, and Chinese count tasks, but this was largely because the Chinese traded off fixation durations with number of fixations. While eye movement behavior tends to be fairly stable across tasks, there was not strong evidence in favor of the idea that culture systematically modulates eye movements other than the tradeoff we have noted between fixation duration and number of fixations in some of the tasks.

Acknowledgments

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