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Eye movements during multiple readings of the same text

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Eye movements during multiple readings of the same text

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Abstract

People often read the same text more than once. Studying eye movements during multiple readings of the same texts provides a unique opportunity to observe the consistency of saccadic landing positions. Eye movements were recorded while 5 people read the same 4 texts more than 40 times, no more than 4 times/day, and never on consecutive trials. Other texts, read only once, were interspersed. Comprehension questions and a change-detection task helped maintain attention in the face of the repetition. There were two main findings: (1) repeated reading produced significant, but modest, changes in global saccadic patterns. The only change found in all readers was a reduction in the proportion of regressions. (2) Saccadic landing positions fell into clusters located at a variety of places with respect to word boundaries, and often across word boundaries. A mixed-strategy model of saccadic guidance (look to the center of words, while trying to maintain fairly uniform saccade lengths), could account for the overall strength of clustering, but not for the variability among cluster locations, suggesting that saccadic landing sites are selected in part on the basis of local text characteristics. The reliable clustering of saccadic landing positions found during multiple readings of the same text opens the way for cluster patterns to be used to study eye movement strategies during reading and overcome at least some of the variability associated with traditional global single-text measures.

Keywords: Eye movements; Saccades; Saccadic eye movements; Reading; Saccadic planning; Attention; Word recognition; Motor planning; Repeated reading

1. Introduction

Effective reading depends on eye movements to control the flow of incoming visual information. The importance of eye movements to reading has inspired many attempts to study, analyze and model eye movement patterns, focusing on the processes that control where and when saccades are made (Epelboim, Booth, & Steinman, 1994, 1997; Engbert, Longtin, & Kleigl, 2002; Kowler & Anton, 1987; Legge, Hooven, Klitz, Mansfield, & Tjan, 2002, 1997; McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1990; Reichle, Rayner, & Pollatsek, 2003; Reilly & O'Regan, 1998; Suppes, 1990). Studies of eye movements during reading are typically based on data obtained from different texts, each read once by a given reader. Data are pooled across the texts, and usually across different readers as well. While pooled observations have led to some interesting generalizations about the relationship between text properties and eye movements, they also introduce variability due to differences among texts or among readers. Several researchers have commented on the considerable variability of reading eye movements, and the obstacles that the variability presents to understanding relationships between text properties and saccadic patterns (e.g., Epelboim et al., 1994; Legge, Klitz, & Tjan, 1997; O'Regan, 1990; Rayner & McConkie, 1976; Suppes, 1990).

An alternative approach to studying eye movements during reading is to avoid pooling across texts, and instead obtain multiple readings of the same text by the same person, analogous to conventional approaches in perceptual psychophysics (Regan, 2000) or oculomotor research (Carpenter, 1992; Kowler, 1990). But reading the same text multiple times is problematic because of the possible influence of memory from the prior readings. Thus, immediate

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decoding of the text might be short-circuited during repeated reading, allowing readers to go through the motions, so to speak, and not be "reading" in the conventional sense (Vitu, O'Regan, Inhoff, & Topolski, 1995).

Despite these concerns, studying repeated reading has value. There are many situations—studying for exams, editing manuscripts or deciphering instructional manuals, for example—in which people choose to read a text multiple times. The preference to re-read when accurate reading is required shows that repeated reading is an active process that serves a useful function, allowing readers to improve text comprehension or fill in gaps in memory for text contents (e.g., Levy, DiPersio, & Hollingshead, 1992). A few studies have been done of eye movements during repeated reading. Data averaged over readers showed that reading the same text between 2 and 5 times usually produced faster reading speeds though a combination of increases in saccade size, decreases in intersaccadic pause durations, and reductions in number of regressive saccades (Hyönä, 1995; Hyönä & Niemi, 1990; Inhoff, Topolski, Vitu, & O'Regan, 1993; Rayner and Raney, 1995).

The present study, like the prior work, examined global characteristics of eye movements during repeated reading. Our main goal, however, was to find what repeated reading might reveal about the planning of saccades. Repeated reading presents a unique opportunity to observe the consistency of saccadic landing sites in the same individual reading the same material many times. If characteristics of the text place strong constraints on saccadic programming, or if certain spatial segmentations of the text into discrete fixations are preferable to others, then saccadic landing positions should cluster around consistent locations across multiple readings of the same text. The locations of such clusters should be informative. While prior work has investigated the effect of text variables, such as word length or ordinal position of letters, on the probability of fixating a location (Epelboim et al., 1994; McConkie et al., 1988; Rayner, 1979; Rayner & McConkie, 1976; Vitu, O'Regan, & Mittau, 1990), repeated reading presents additional options for analysis because it is possible to examine how saccadic landing positions are distributed across a sequence of words, in the context of the whole text. This may reveal influences of text characteristics on saccades that have not been apparent in prior work using texts that are read only once. The long-range challenge, of course, will be to determine whether any such influences are restricted to repeated reading, or whether they apply more generally.

Our interest in determining the consistency of landing positions led us to use procedures that would encourage readers to keep attending to the text even after several readings. To this end, a given text was read no more than 4 times per day (with a total of 44 readings/text), never on consecutive trials, and with new texts interspersed. In addition, comprehension questions were asked each day, and a change-detection task was included on some days.

Repeated reading produced surprisingly modest changes in global characteristics of saccadic eye movements, with individuals maintaining their signature patterns of saccade sizes and intersaccadic pause durations despite the extensive repetition. The most consistent change in saccades was a reduction in regressions, suggesting that when reading a text for the first time, the pattern of forward saccades sets a pace that is too fast for optimal comprehension. The analyses also showed significant clustering of saccadic landing positions in a variety of places with respect to word boundaries, often bridging the boundaries between words. These results show that repeated reading has the potential to reveal aspects of reading strategies and saccadic control that would not be apparent from data pooled across different texts read once.

2. Methods

2.1. Subjects

Five paid volunteers were tested (R1, R2, R3, R4, and R5), all Rutgers undergraduate students with normal vision and no spectacle correction. They were not told the purpose of the experiment.

2.2. Stimulus display

Stimuli were generated either by an SGI Iris O2 workstation and displayed on an SGI GDM 17-E21 17" color monitor, or by a PC and displayed on a Dell 17" color monitor. Displays were located directly in front of the subject's right eye at a distance of 119 cm. Resolution was 108 pixels/deg at a refresh rate of 72 Hz.

2.3. Eye movement recording

Two-dimensional movements of the right eye were recorded by a Generation IV SRI Double Purkinje Image Tracker (Crane & Steele, 1978). The subject's left eye was covered and the head was stabilized on a dental biteboard.

The voltage output of the Tracker was fed online through a low pass 50 Hz filter to a 12-bit analog to digital converter (ADC). The ADC, controlled by a PC, sampled eye position every 5 ms. The digitized voltages were stored for later analysis. The PC controlled the timing of the stimulus display via a serial link to the SGI computer. Voltage from a photocell that recorded stimulus onset and offset directly from the display monitor was fed into a channel of the ADC and recorded along with the eye position samples to ensure accurate temporal synchronization between stimulus display and eye movement recording.

Tracker noise level was measured with an artificial eye after the tracker had been adjusted so as to have the same first and fourth image reflections as the average subject's eye. Filtering and sampling rate were the same as those used in the experiment. Noise level, expressed as a standard deviation of position samples, was .4′ for horizontal and .7′ for vertical position.

Recordings were made with the tracker's automatically movable optical stage (autostage) and focus servo disabled. These procedures are necessary with Generation IV Trackers because motion of either the autostage or the focus servo introduces larger artifactual deviations of Tracker output. The focus servo was used, as needed, only during intertrial intervals to maintain subject alignment. This can be done without introducing artifacts into the recordings or changing the eye position/voltage analog calibration. The autostage was permanently disabled because its operation, even during intertrial intervals, changed the eye position/voltage analog calibration.

2.4. Texts

Texts were taken from a variety of sources including the *Washington Post*, *Yahoo! News*, the *Associated Press*, and introductory college textbooks. All texts contained a maximum of 43 characters per line and either 8 or 9 lines. Characters were displayed at a spacing of 4.1/deg using a fixed-width font, and 1.4 lines/deg. Texts contained an average of 57.4 words (*SD* 5.9) and words had an average length of 5.2 letters (*SD* 2.7).

Three texts ("The Mummy," "Voters," and "Space Station") were each presented 44 times throughout the experiment, and will be referred to as Repeated Texts. In addition, 44 texts were presented once (Single Texts). In some sessions (Task sessions, see below) the Repeated Texts were presented either in their original form (18 trials/text) or were modified (6 trials/text) either by altering syntax, introducing synonyms, or changing spelling. A maximum of 4 alterations/text were made.

A fourth Repeated Text ("Clipping") was also included and tested in the same number of trials and in the same experimental sessions as the other 3 Repeated Texts. Its content was technical, and hence harder to understand. It was included to verify that any effects of repetition would also be found with a text that would not be easily understood even after several readings. Because of its different character, data from this difficult text will be presented separately from the other three. The four repeated texts can be seen in Fig. 5, Figs. S1, S6 and S11.

2.5. Procedure

Before each trial a fixation cross was shown in the upper left corner of the display, corresponding to the location of the first character. Subjects fixated the cross and pressed a button when ready to begin the trial. After a 500 ms delay the fixation cross disappeared and the text was presented. The text remained on the screen for 22 s. This value was chosen based on pilot sessions using different texts to allow enough time to complete the texts during the first reading.

Subjects were instructed to read the text, to avoid re-reading a line of text that they had completed, and to remain fixated on the last character of the passage if they finished reading before the trial ended. A few (3–5) comprehension questions about details of the texts were asked after each session. (Example: for "The Mummy," Figs 7–11, "What type of liquid was poured into the skull?" A: an acidic liquid.) Readers were not told whether their answers were correct.

2.6. Experimental sessions

Experimental sessions contained 20 trials. There were two types of sessions, *Read* and *Task*. *Read sessions* consisted of 16 presentations of Repeated Texts (4 texts, 4 times each), as well as 4 presentations of Single Texts. Texts were randomly ordered with the constraint that the same Repeated Text could not appear in consecutive trials. *Task sessions* were the same except 4 of the trials with the Repeated Texts were modified as described above (see section Section 2.4). The same Repeated Text, in either its original or modified form, was never presented in consecutive trials. In Task sessions, subjects reported whether any changes were detected after each Repeated Text trial. No feedback as to the correctness of these reports was given. As in the Read sessions, comprehension questions were asked at the end of the session.

Eleven experimental sessions were run in the following order: Read ($n = 2$ sessions), Task ($n = 4$), Read ($n = 3$), and finally Task again ($n = 2$). Occasional trials were omitted because eyetracker lock was lost during more than one-third of the trial.

2.7. Detection and measurement of saccades

The beginning and end positions of saccades were detected by means of a computer algorithm employing an acceleration criterion. Specifically, eye velocity was calculated for two overlapping 15 ms intervals. The onset time of the second interval was 5 ms later than the onset time of the first. The criterion for detecting the beginning and end of a saccade was determined for each subject. Saccades as small as the microsaccades that may be observed during maintained fixation (Steinman, Haddad, Skavenski, & Wyman, 1973) could be reliably detected by the algorithm.

3. Results

3.1. Comprehension and speed

3.1.1. Comprehension

Attentive reading was encouraged by questions about text content ($n = 37$) that were asked after each session. The responses were quite accurate for Single Texts (89% correct for R1, 85% for R2, 89% for R3, 89% for R4, and 85% for R5) and slightly better for four of the readers for the Repeated Texts (90% for R1, 90% for R2, 80% for R3, 100% for R4 and 90% for R5).

Performance on the change-detection task in the separate Task sessions (see Section 2) did not produce such high levels of success. Four subjects detected about 60–70% of the changes (R1: 64%; R3: 60%; R4: 71%; R5: 64%); R2 performed more poorly (41%). There were also a few (2–16, depending on subject) false alarms. The failure to detect about a third of the changes shows that even after several readings, the representation of the content of the Repeated Texts was still incomplete. The analysis of eye movements, which follows below, does not include the task trials in which changes to the text were made.

3.1.2. Reading speed

Reading speed was faster for Repeated Texts than for Single Texts (Fig. 1, left). Individuals differed in reading speed, with R2 reading the fastest and showing the largest increase in speed for the Repeated Texts. For R2 Repeated Texts were read 22% faster than Single Texts in the Read sessions and 12% faster in Task sessions. The changes in reading speed for Repeated Texts were smaller for the other 4 readers. R2, who had the fastest reading speed, also had the most errors in the change detection task.

The same pattern of individual differences can be seen in the trial-by-trial changes in reading speed for the individual texts, shown for Read sessions in Fig. 1 (right side). For R1, R2, and R5 reading speed can be seen to increase over trials, with slopes of straight lines fit to each function ranging from .2 to .6 characters/second per repetition. R3 and R4 showed little change in reading speed across trials (slopes ranged from −.2 to .15). Finding little or no change in reading speed with repetition is consistent with the emphasis placed on comprehension and reading accuracy (Hyönä, 1995).

3.2. Global characteristics of saccades

Global characteristics of saccades are shown in Fig. 2, which compares values for Single and Repeated Texts in both the Read and the Task sessions. Fig. 2 shows sizes of forward saccades preceded by other forward saccades (top graphs) and the duration of pauses between forward saccades (middle graphs). Forward saccades following regressions were not included. The bottom graphs show the proportion of regressions, where proportion of regressions = # regressions/(# regressions + # forwards), and the number of forward saccades is again restricted to forward saccades preceded by other forward saccades. The occasional regressions needed when the final forward saccade overshot the end of a line were not included (these regressions were followed by reset saccades made to the next line). The global analysis below also did not include instances in which an entire line was re-read, nor the very first trial in which each Repeated Text was read.

3.2.1. Individual differences

Individual differences were prominent and were maintained across experimental manipulations (Repeated Texts vs. Single Texts; Task vs. Read). For example, R2 and R3 made the largest forward saccades (∼8–10 characters) and had the longest intersaccadic pause durations (∼265–300 ms between pairs of forward saccades). R5 made the smallest saccades with the shortest pause durations. R1's and R4's saccades fell between these two extremes. There were also individual differences in the proportion of regressions (Fig. 2, bottom graphs) that did

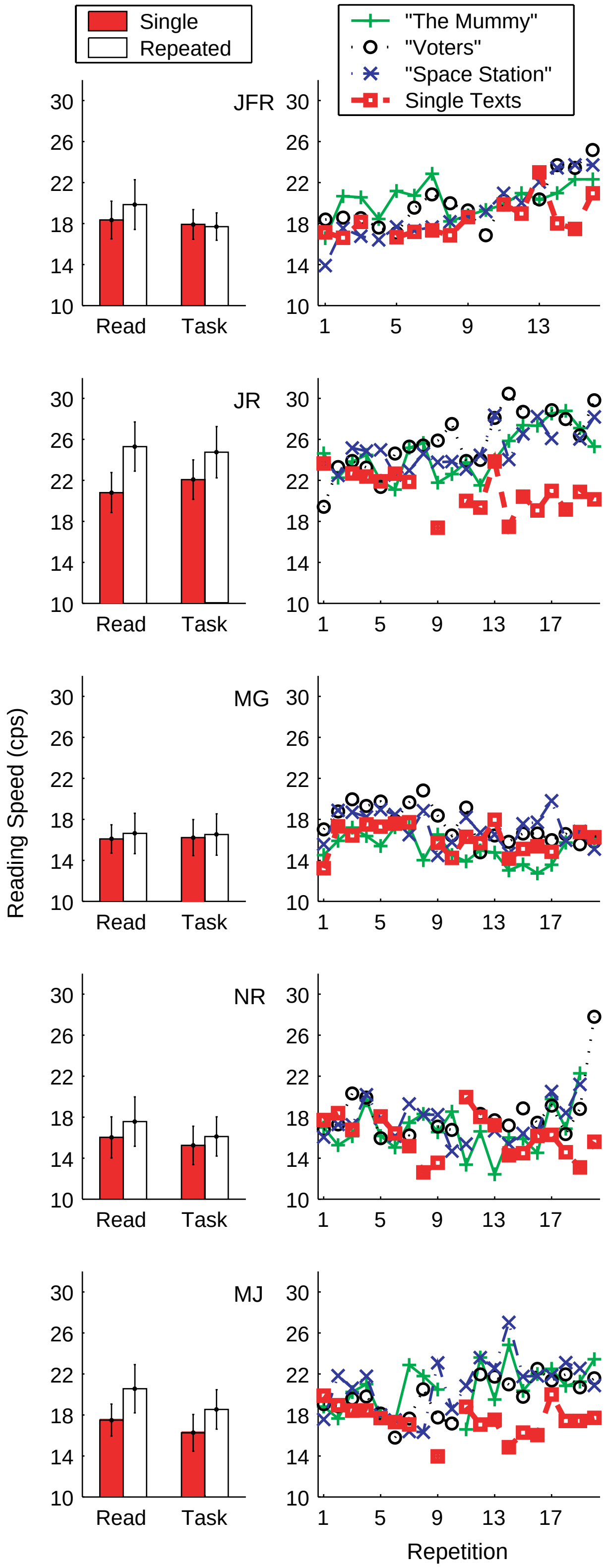

Fig. 1. (Left) Mean reading speed for Single Texts (left bars in Read and in Task) and Repeated Texts (right bars in Read and in Task) in characters/second (cps). Error bars show ±1 SD. Each mean is based on approximately 20 trials. (Right) Individual trial reading speeds as a function of repetition number for the 3 Repeated Texts ("The Mummy," "Voters," and "Space Station") and all Single Texts in Read sessions.

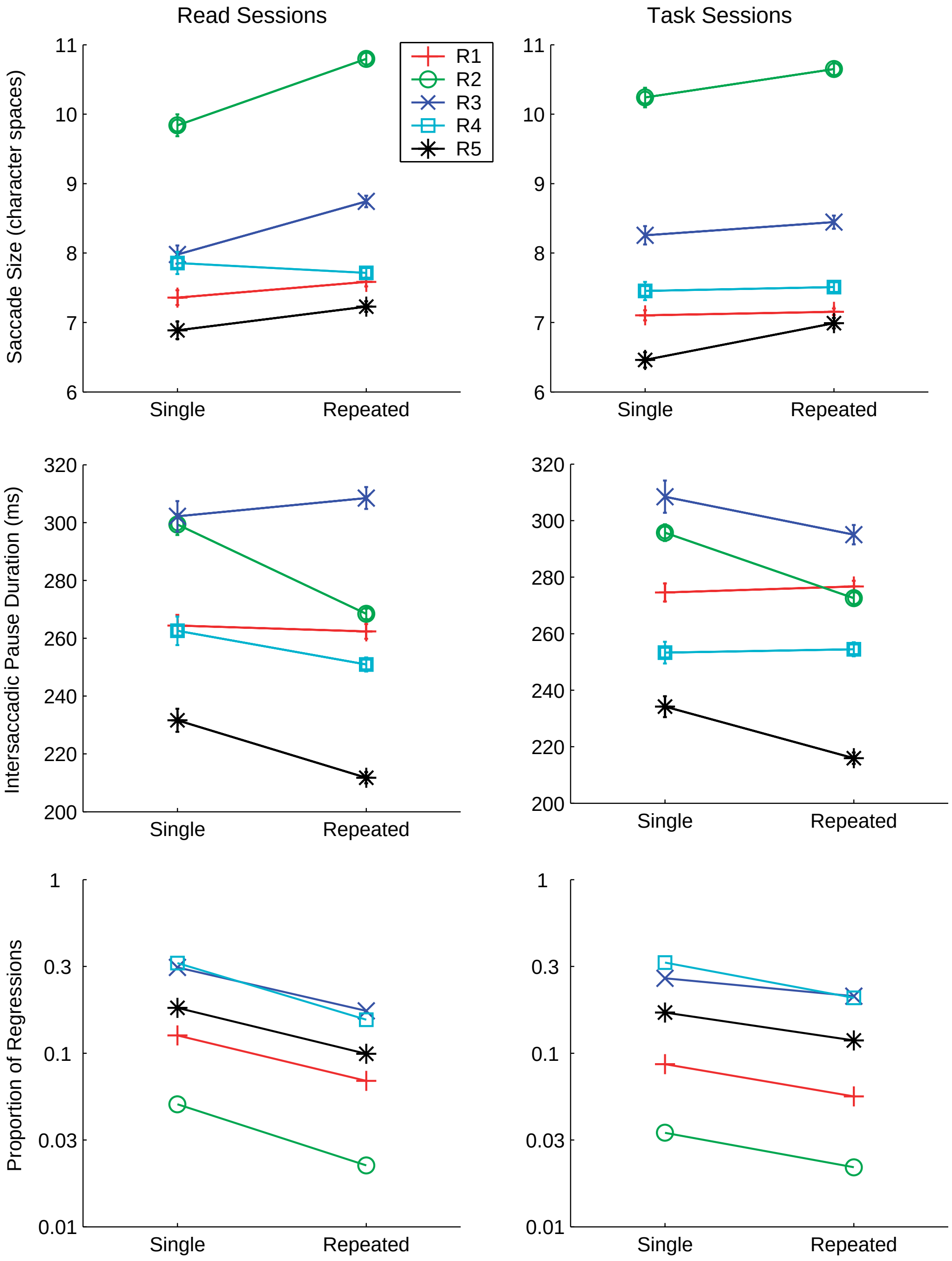

Fig. 2. Mean size of forward saccades (top), mean intersaccadic pause duration between forward saccades (middle), and proportion regressions (bottom) [where proportion regressions = # regressions/(#forward saccades + # regressions)] for Single and Repeated Texts, and for Read Sessions (left) and Task Sessions (right). Standard errors are smaller than the plotting symbols. Each mean is based on about 400–1500 saccades. Reset saccades, and forward saccades that followed regressions, were not included.

not correlate with the sizes or pause durations of the forward saccades.

3.2.2. Single vs. repeated texts (forward saccades)

Three readers (R2, R3, and R5) made significantly larger saccades when reading Repeated Texts than when reading Single Texts ($p < .01$) and the differences were small (1 character for R2; less for the others) (Fig. 2, top). For R2 and R3 differences in saccade size between Repeated and Single texts were larger during the Read sessions than during the Task sessions (significant interaction between type of text and type of session; $p < .05$), an indication of their more careful reading during the Task sessions. There was no consistent effect of repetition on the duration of pauses between forward saccades (Fig. 2, middle). Only R2 and R5 had significantly shorter intersaccadic pause durations with the Repeated Texts ($p < .01$). Their pause durations decreased by about 25 ms.

The differences in mean saccade sizes while reading Repeated Texts found for 3 of the readers (R2, R3, and R5)

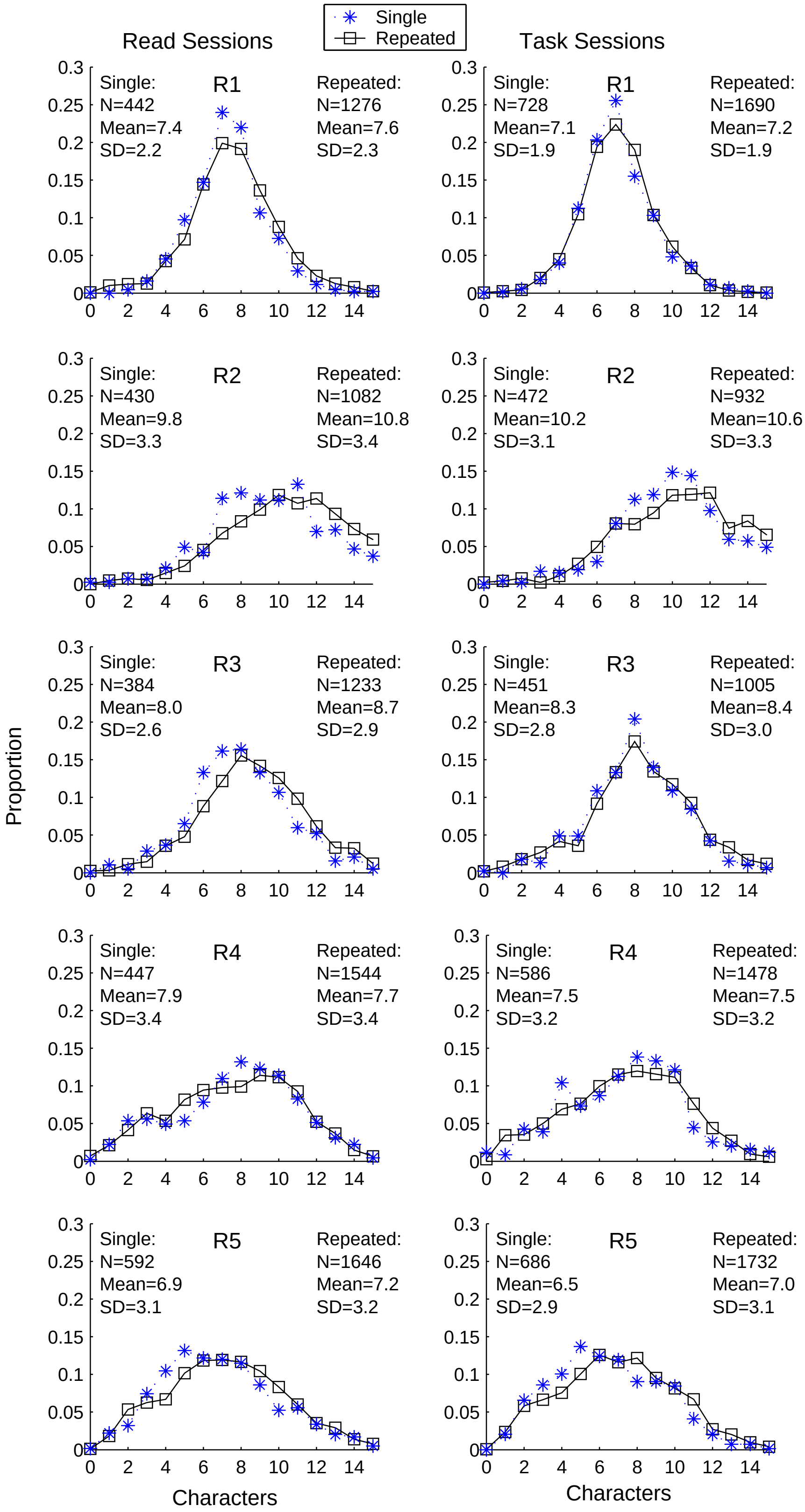

Fig. 3. Proportion of forward saccades of different sizes in characters for Repeated and Single Texts, Read and Task sessions.

could be due either to a shift in the entire distribution of saccade sizes or to an emergence of a separate population of larger saccades. Examination of the distributions of sizes of forward saccades (Fig. 3) shows that the distributions for Repeated and Single Texts were quite similar in shape, and the small increase in mean saccade size for R2, R3, and R5 was due to an overall shift in the distribution to larger saccades.

3.2.3. Regressions

Readers differed in how often they made regressions, but all made fewer regressions with Repeated Texts, particularly in the Read condition. In contrast to the individual differences in the effects of repetition on forward saccades, described above, the proportional decrease in the occurrence of regressions with the Repeated text was quite similar for everyone (Fig. 2, bottom graphs, shows parallel functions for proportion of regressions on a logarithmic axis). The differences between the proportion of regressions with Single and Repeated Texts were significant in all cases except R2's Task sessions. In addition, 3 readers (R1, R3, and R5) showed no change in the size of the regressions with repetition (Fig. 4). R4 made smaller regressions during the reading of Repeated Texts. R2 made few regressions and the sizes were far more variable than for the other readers.

3.2.4. Changes in saccade parameters with repetition

In addition to evaluating the effects of repetition by comparing reading of the Repeated and Single Texts, we also examined how saccades with Repeated Texts changed over experimental sessions. Fig. 5 compares saccade sizes, intersaccadic pauses and proportions of regressive saccades for the first two Read sessions (denoted "Early Read" in the figure) with the final 3 Read sessions ("Late Read"). (A set of Task sessions was run between Early and Late Read; see Section 2 for details.) Differences in saccadic characteristics between Early and Late Read sessions were modest. R1 showed a significant increase in saccade size (from 7.4 to 7.7 characters; $p < .05$), and R2 and R5 showed significant decreases in intersaccadic pauses (a decrease of 24 ms for R2 and 15 ms for R5, $p < .001$). R1, R4, and R5 showed small (4–6%) but significant ($p < .01$) decreases in the proportions of regressions.

3.2.5. Read vs. Task

Fig. 2 shows that differences between saccades in Read and Task sessions were small. The 3 readers with the shortest saccades (R1, R4, and R5) made significantly shorter saccades (about 0.5 character) in Task sessions than in Read sessions ($p < .01$). Their saccades were also shorter even for the interspersed trials with the Single Texts, in which no changes had to be detected, presumably reflecting a global change in saccadic planning influenced by the surrounding trials with Repeated Texts. R2 and R3 had shorter saccades in Task sessions only for the Repeated Texts. Intersaccadic pause durations were not affected much by type of session. Only R1 had significantly longer pause durations during the Task than during the Read sessions ($p < .01$). Regressions were slightly more frequent in the Task sessions.

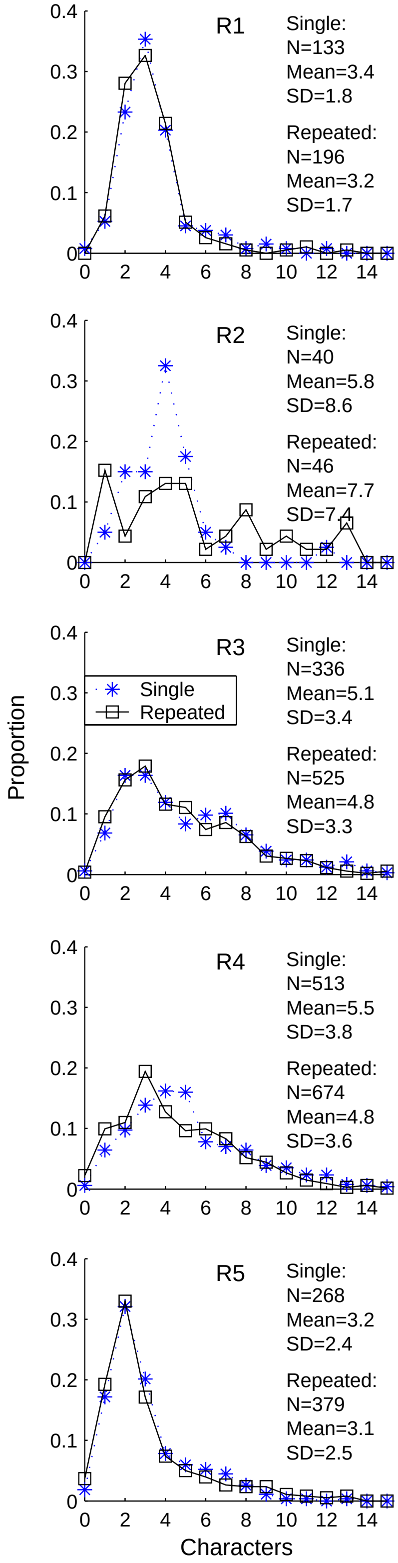

Fig. 4. Proportion of regressions of different sizes in characters for Repeated and Single Texts. Data are pooled over Read and Task Sessions.

3.2.6. Repeated reading of a difficult text

One Repeated text ("Clipping," see Section 2) was included to find out whether any effects of repeated reading would extend to texts whose meaning was obscure due to its highly technical content, which was unfamiliar to our subjects. Because this text differed in its semantic character from the other texts, data from this text were not included in the global analyses above. Saccadic characteristics for this text were similar to those found for the other Repeated Texts (see data for individual texts in Table 1). The main

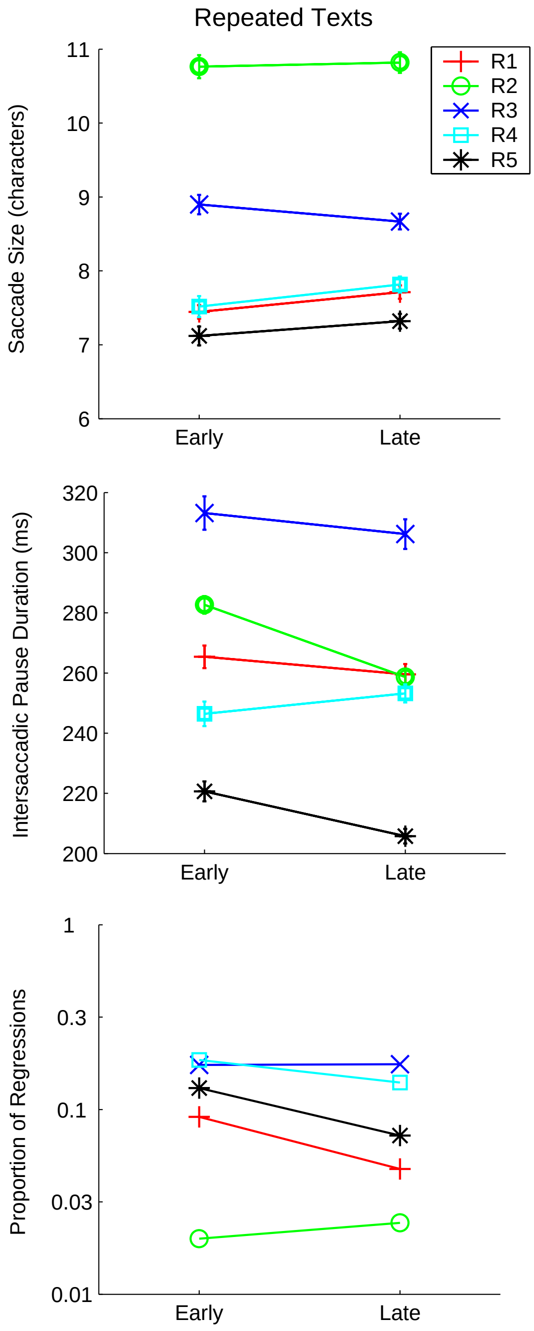

Fig. 5. Mean size of forward saccades (top), mean intersaccadic pause duration between forward saccades (middle), and proportion regressions (bottom) [where proportion regressions = # regressions/(#forward saccades + # regressions)] for the two Early Read Sessions and the 3 Late Read Sessions. Reset saccades, and forward saccades that followed regressions, were not included.

Table 1
Forward saccade properties for each Repeated Text and pooled over Repeated Texts and Single Texts

	Forward saccades			Regressions
	Size (*SD*)	ISP (*SD*)	*N*	P(REG)
The Mummy				
R1	7.4 (2.1)	270 (94)	919	0.05
R2	10.9 (3.5)	269 (65)	668	0.01
R3	8.4 (2.9)	307 (121)	772	0.13
R4	7.5 (3.3)	254 (93)	990	0.15
R5	7.3 (3.2)	211 (78)	986	0.09
Voters				
R1	7.2 (2.1)	272 (87)	1055	0.04
R2	10.8 (3.2)	279 (66)	676	0.00
R3	8.7 (3.2)	307 (106)	732	0.10
R4	7.5 (3.3)	250 (93)	1021	0.12
R5	6.9 (3.0)	221 (86)	1270	0.05
Space station				
R1	7.4 (2.1)	272 (80)	1080	0.03
R2	10.6 (3.4)	266 (64)	733	0.01
R3	8.7 (2.8)	295 (137)	799	0.13
R4	7.8 (3.3)	255 (101)	1086	0.13
R5	7.1 (3.2)	209 (80)	1211	0.07
Clipping				
R1	7.2 (2.0)	286 (90)	1068	0.07
R2	10.7 (3.6)	278 (63)	724	0.02
R3	8.8 (3.3)	316 (129)	719	0.15
R4	7.8 (3.5)	251 (101)	1043	0.16
R5	6.9 (3.2)	228 (100)	1141	0.10
Single Texts				
R1	7.2 (2.1)	271 (83)	1170	0.06
R2	10.1 (3.2)	297 (70)	902	0.02
R3	8.1 (2.7)	306 (113)	835	0.19
R4	7.6 (3.3)	257 (98)	1033	0.24
R5	6.7 (3.0)	233 (97)	1278	0.11
The Mummy, Voters, Space Station Combined[a]				
R1	7.3 (2.1)	271 (87)	3054	0.04
R2	10.7 (3.4)	271 (65)	2077	0.01
R3	8.6 (3.0)	303 (123)	2303	0.12
R4	7.6 (3.3)	253 (96)	3097	0.14
R5	7.1 (3.1)	214 (82)	3467	0.07

Table shows sizes of forward saccades preceded by both forward and reset saccades (in characters) and pauses between forward saccades (ISP) preceded by both forward saccades and reset saccades (in ms). Proportion of regressive saccades [P(REG)] is equal to the the number of regressions divided by the sum of forward saccades and regressions. Data were pooled over Read and Task Sessions.

[a] Clipping was not pooled with the other texts due to its different semantic character. See Section. 2.

difference between this difficult text and the other three repeated texts was a higher frequency of regressions and longer (∼10 ms) intersaccadic pauses.

3.2.7. Saccadic landing positions within words

Prior studies of eye movements during reading have shown that the first saccade arriving at a word lands, on average, near or (for longer words) slightly to the left of the center of words (McConkie et al., 1988; Rayner, 1979; Vitu et al., 1990). This observation was confirmed, both with the Repeated and the Single Texts (Fig. 6). Thus, landing position within-words was not influenced by the repetition.

3.2.8. Summary of global characteristics

The analyses of eye movements showed that reading texts repeatedly, with or without the change detection task, had significant, but generally modest, effects on the eye movements. Overall, Repeated Texts were read with fewer regressions by all readers, and slightly larger saccades and shorter intersaccadic pauses by some.

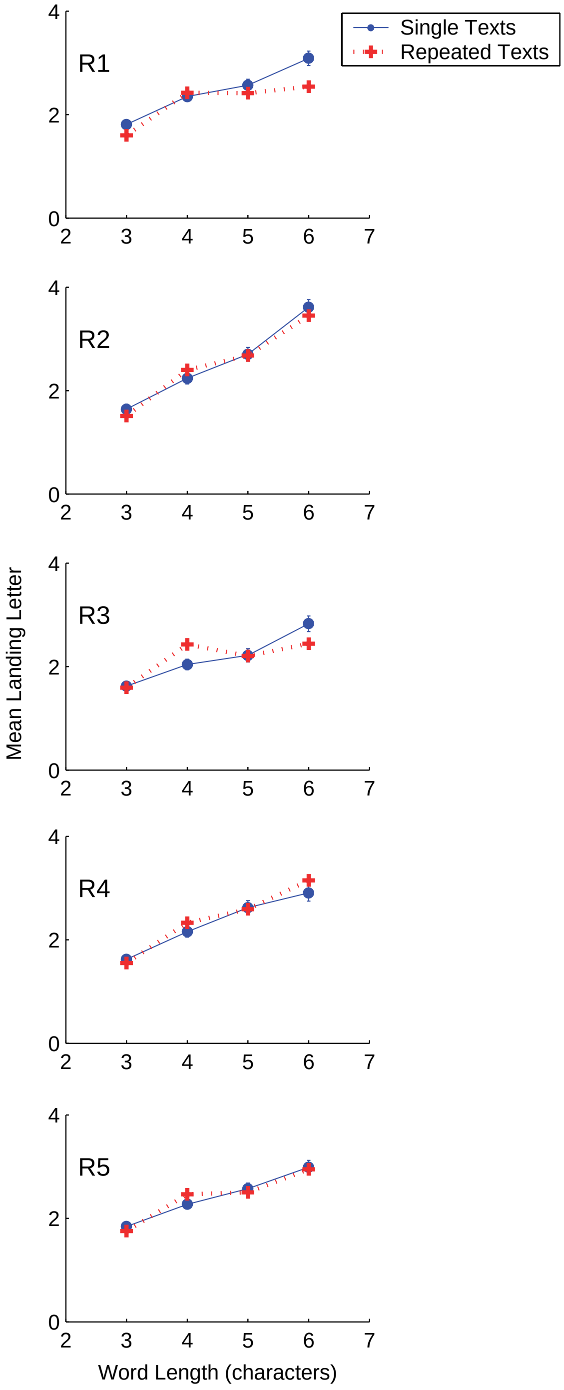

Fig. 6. Mean landing letter of the first saccade into a word as a function of word length for Single and Repeated Texts. Landing letter 0 on the ordinate represents the space prior to the first letter of a word. Error bars when larger than the plotting symbols show ±1 SE. Each mean is based on ~1000 observations.

3.3. Local characteristics of saccades: Clustering

A major goal of this study was to determine whether consistent patterns of saccadic landing positions would be obtained over repeated readings of the same text. To examine the consistency in landing positions, "cluster graphs" were created showing the number of times a given reader's saccades landed on each character (including blank spaces) in a given text. Consistency in landing positions would be indicated by finding that saccadic endpoints clustered around particular characters of the text.

Cluster graphs for reading "The Mummy" (Art, 1993) are shown in Fig. 7–11. Each "+" symbol represents a single saccadic endpoint. (Ignore for the moment the shaded bars; these will be described below.) The first cluster on each line shows the endpoints of the reset saccades.

Visual inspection of Figs. 7–11 shows clustering of saccadic endpoints in at least a portion of the text for each reader. Clustering was strongest for R1 (Fig. 7), R2 (Fig. 8) and R5 (Fig. 11), however, even in their data some regions showed little clustering. The distance between prominent clusters was typically about 7–9 characters. Distances were usually smaller towards the end of each line, indicating some effect of line termination on saccades. Supplemental Figs. S1–S15 show the cluster graphs for the three remaining texts. The characteristics of those cluster graphs are similar to those for "The Mummy."

3.3.1. Statistics of clustering: Repeated vs. single texts

If the observed clustering reflected a tendency to select the size of each forward saccade by sampling from a single distribution of saccade sizes, whose parameters were independent of the local characteristics of the text, then the same degree of clustering should appear in data pooled over the Single Texts. If, on the other hand, clustering is due to the influence of the local characteristics of the text on landing positions, then clustering should be more prominent for the Repeated Texts due to the consistency of local characteristics. Fig. 12 shows the cluster graph for R1 obtained by compiling data from his Single Texts. Clustering appears weaker than found for R1 reading Repeated text (e.g., Fig. 7, Figs. S1, S6, S11). Similar results were found for the other readers.

To compare the extent of clustering in Single and Repeated Texts the following was done: First, using the data shown in the cluster graphs, the frequency of landing at any given character location was found by dividing the number of landings on a given character location by the number of trials included in the cluster graph. This was done separately for each reader and for each of the Repeated Texts, and as well as for the individual reader's data aggregated across all Single Texts. For example, landing on a given character location a total of 10 times in 40 trials of reading "The Mummy" would yield a frequency value of .25; landing on this same location in each trial would produce a frequency value of 1. After the frequencies were calculated for each character location, including the spaces between words, histograms were plotted showing how often different frequency values were observed. In these histograms, the abscissa shows the frequency value, and the ordinate shows the proportion of times a given frequency value was obtained. Histograms for "The Mummy" are compared to those for the pooled Single Texts in Fig. 13. Histograms for the remaining Repeated Texts are shown in Figs. S16–S18.

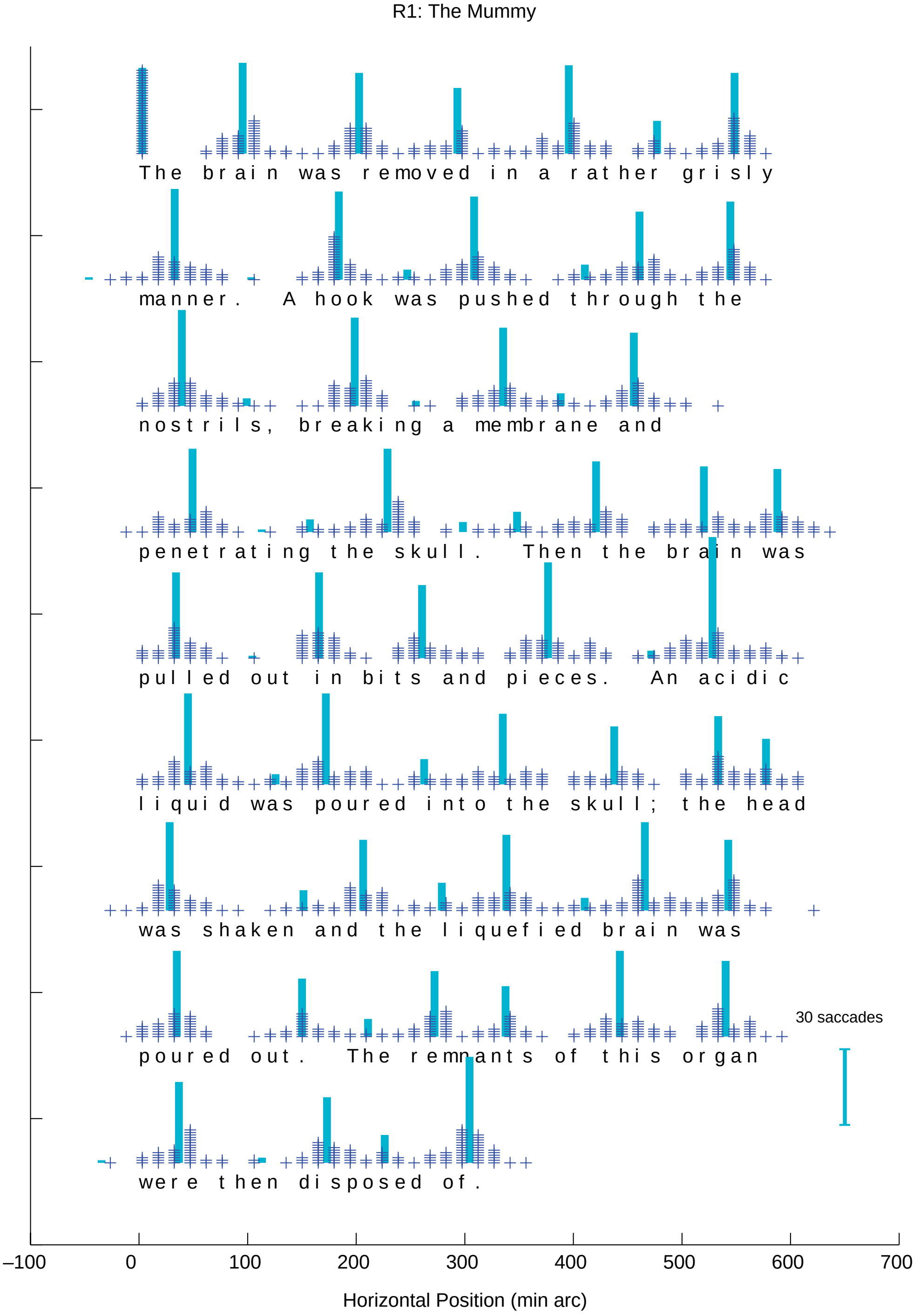

Fig. 7. Cluster graph showing landing positions of all saccades (+) (Read and Task sessions included) for R1 reading "The Mummy." Regressions and forward saccades following regressions are not included. The large vertical pile of symbols over the very first letter in the text shows the start position of the initial saccade. The cluster at the beginning of each subsequent line shows the endpoints of the reset saccades. Location 0 on the abscissa is the first character of each line. The shaded bars are the results of the mean shift clustering procedure (see text).

The histograms show that the Repeated Texts had a greater proportion of character locations that were visited frequently, as well as a greater proportion that were visited infrequently, than Single Texts. This is a signature characteristic of clustering. Single Texts had a greater proportion of character locations that were landed on with a moderate frequency. Statistical tests performed on the number of times different frequency values were observed for Single vs. Repeated Texts showed that the differences between Repeated and Single Texts for "The Mummy" (Fig. 13) were significant for everyone except R4 ($p < .001$ for R1, R2, and R5; $p < .01$ for R3). Results were similar for the other 3 Repeated Texts (Figs. S16–S18) ($p < .001$ for R1, R2, R3, and R5 for all texts; for R4, $p < .01$ for "Voters" and "Clipping", $p < .025$ for "Space Station").

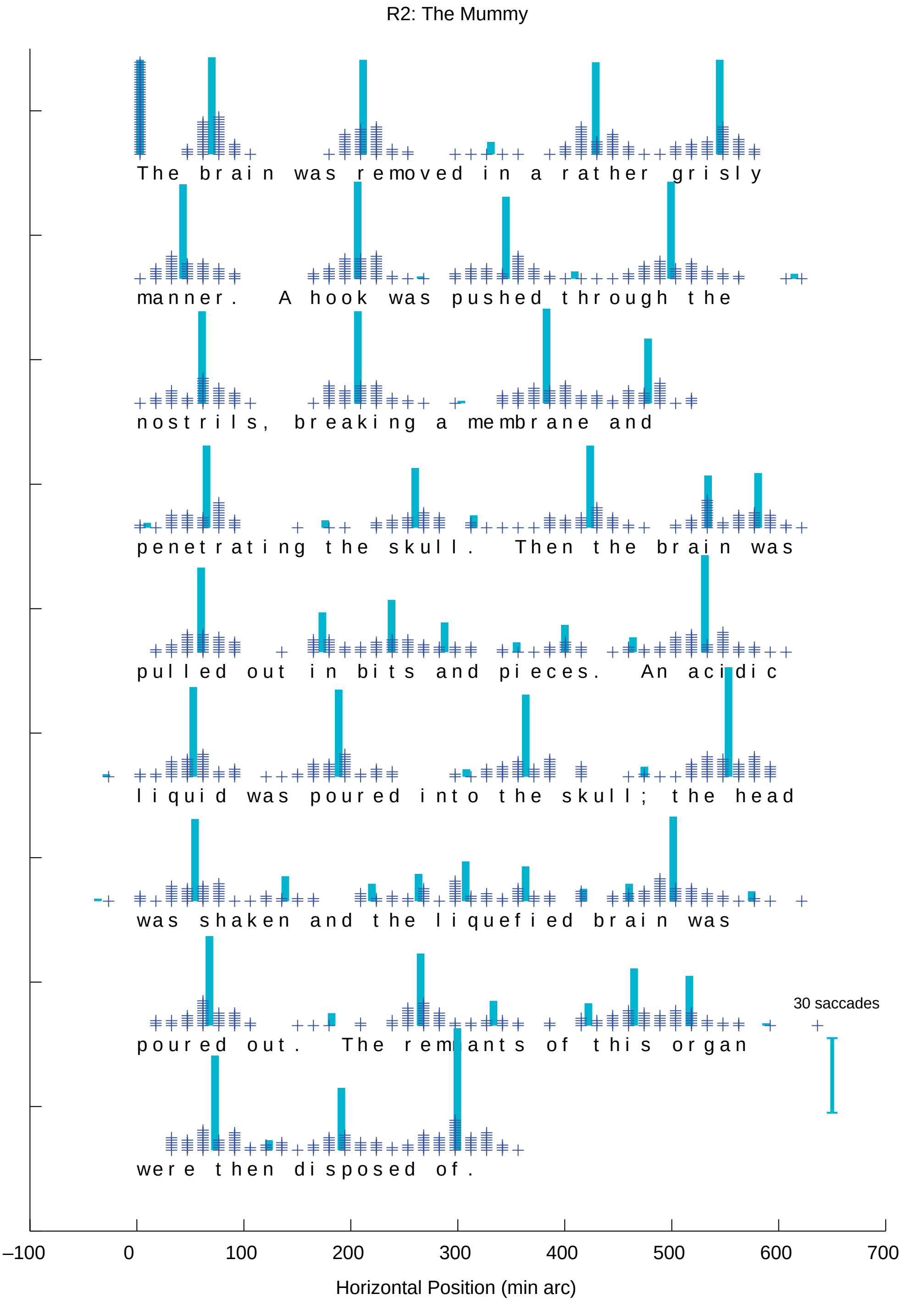

Fig. 8. Cluster graph showing landing positions of all saccades (+) (Read and Task sessions included) for R2 reading "The Mummy." Regressions and forward saccades following regressions are not included. The large vertical pile of symbols over the very first letter in the text shows the start position of the initial saccade. The cluster at the beginning of each subsequent line shows the endpoints of the reset saccades. Location 0 on the abscissa is the first character of each line. The shaded bars are the results of the mean shift clustering procedure (see text).

These analyses confirm that Repeated Texts and Single Texts differed in terms of the amount of clustering of saccadic landing positions. Thus, the clustering observed with the Repeated Text was not due solely to consistencies in saccade size. Rather, local characteristics of the text played a role in determining where the eye landed.

3.3.2. Locations of clusters

To characterize the locations of clusters, we used a "mean shift" algorithm, which was developed for pattern recognition (see Comaniciu & Meer, 2002) and recently applied to the analysis of fixation positions in visual scenes (Santella & DeCarlo, 2004). Briefly, the algorithm shifts individual sacc-

Fig. 9. Cluster graph showing landing positions of all saccades (+) (Read and Task sessions included) for R3 reading “The Mummy”. Regressions and forward saccades following regressions are not included. The large vertical pile of symbols over the very first letter in the text shows the start position of the initial saccade. The cluster at the beginning of each subsequent line shows the endpoints of the reset saccades. Location 0 on the abscissa is the first character of each line. The shaded bars are the results of the mean shift clustering procedure (see text).

adic landing positions towards nearby locations where the density of landings is highest. It does this by iteratively shifting each landing position to a location that is equal to the weighted mean of all the neighboring locations. The weighting function used was a Gaussian centered on the given landing position with standard deviation set to 1 character. Thus, the standard deviation of the Gaussian determines the spatial scale of the clustering. A standard deviation of 1 character is about 15% of the average saccade size, a value that is compatible with the expected variability of saccades (Kowler & Blaser, 1995). After the “mean shift” was applied to each landing position in a line of text, the entire procedure was then repeated on the new shifted landing positions. The process continued until the results converged. The criterion for convergence was a difference in the results of successive iterations of 0.1%.

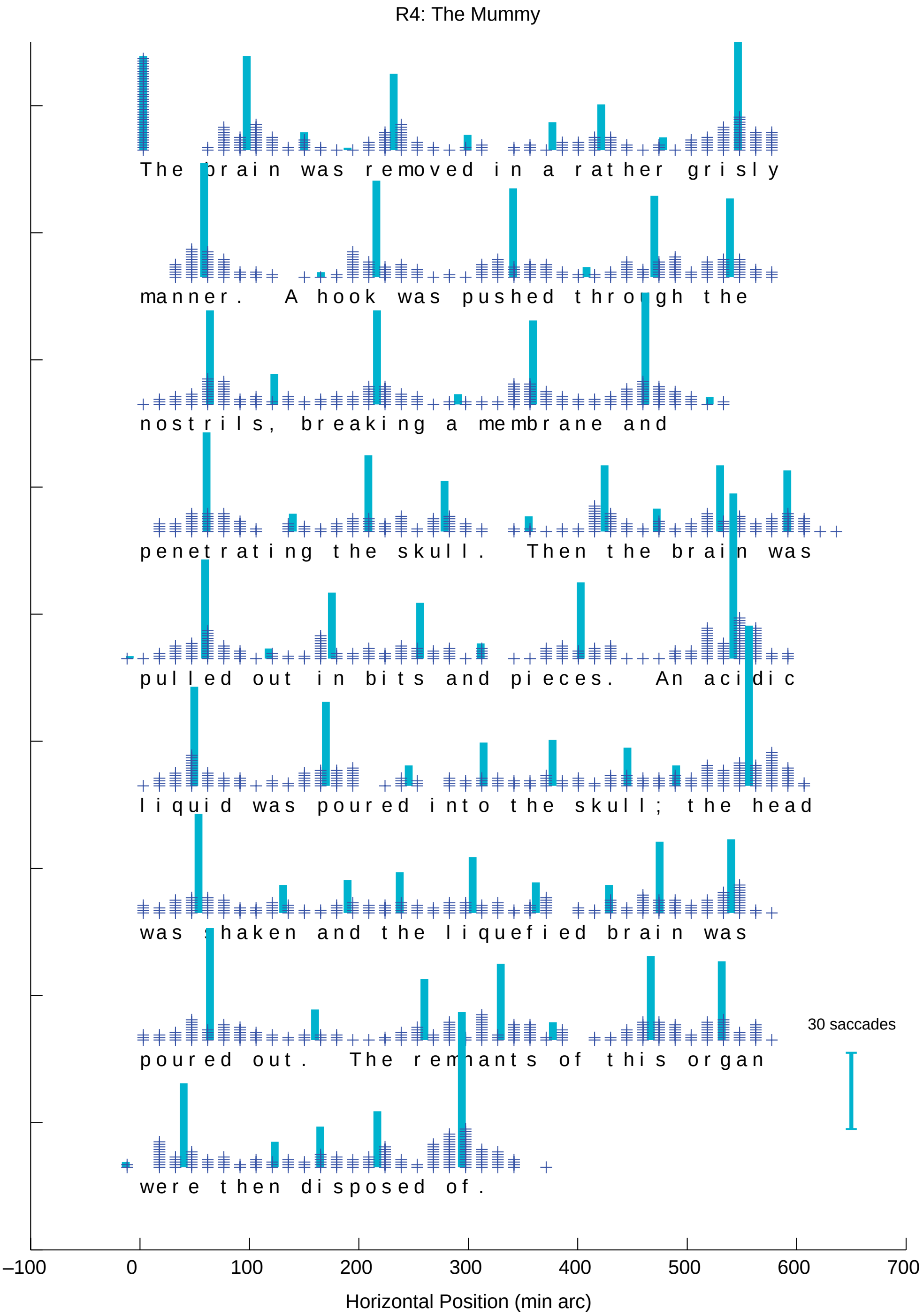

Fig. 10. Cluster graph showing landing positions of all saccades (+) (Read and Task sessions included) for R4 reading "The Mummy." Regressions and forward saccades following regressions are not included. The large vertical pile of symbols over the very first letter in the text shows the start position of the initial saccade. The cluster at the beginning of each subsequent line shows the endpoints of the reset saccades. Location 0 on the abscissa is the first character of each line. The shaded bars are the results of the mean shift clustering procedure (see text).

The clustering algorithm was applied to all the landing positions shown in the cluster graphs, and the results are shown by the shaded bars in Figs. 7–11. Examination of the shaded bars, as well as the pattern of individual landing positions in the cluster graphs, shows that there is no simple characterization of the locations of the clusters, either within or across readers. Clusters were not separated by a constant number of characters, nor were their locations suggestive of word-by-word reading. Clusters were located at various places relative to word boundaries. Using "The Mummy" (Figs. 7–11) as the example, cluster centers can be seen near the middle of a word (e.g., "breaking" on line 3), or toward the end of a word ("through", line 2). Some clusters were centered on short words ("this," line 8), but other short words were seldom fixated ("the," which appears twice on line 4; "was," line 2; "into," line 6). Some cluster centers overlapped word bound-

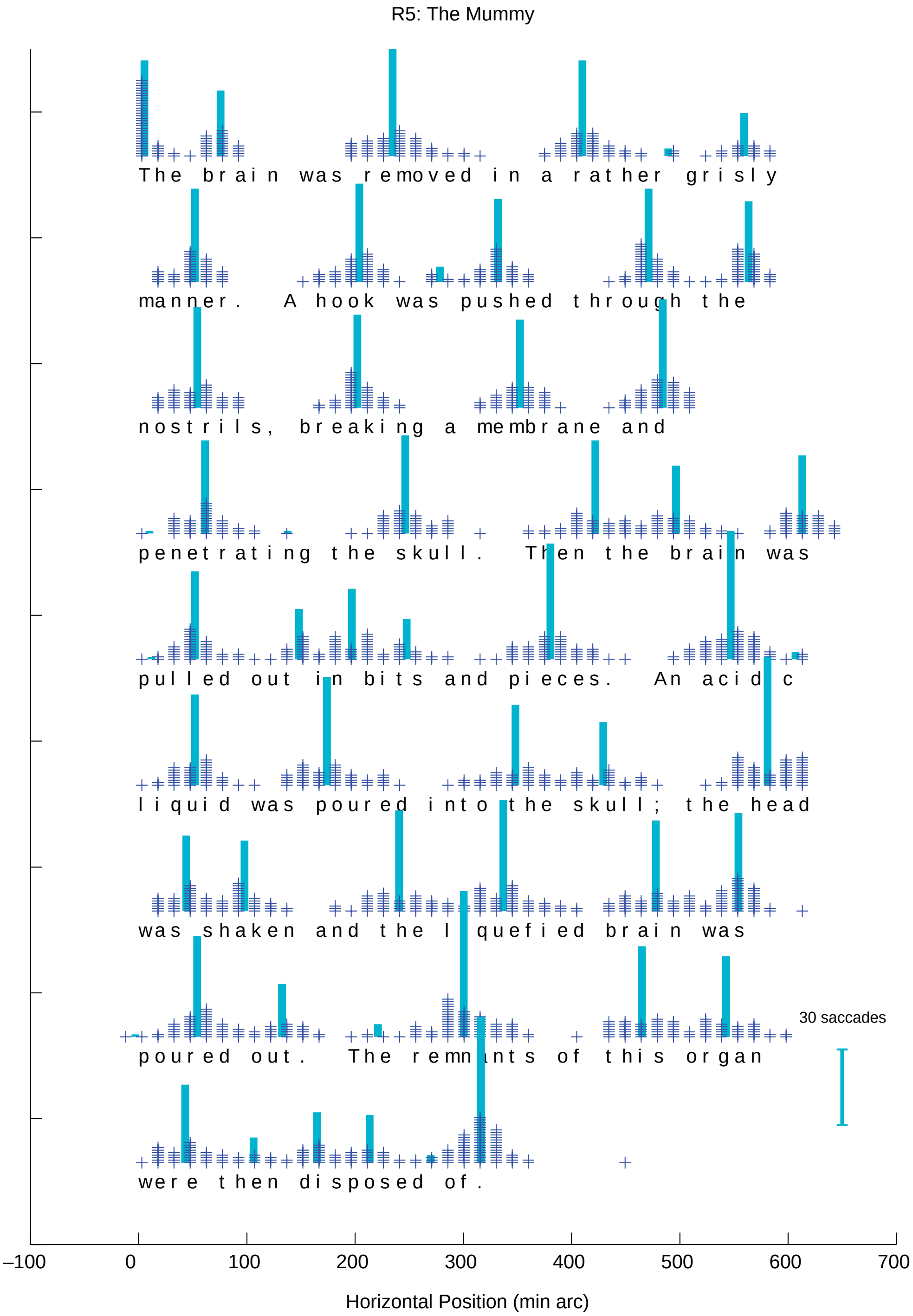

Fig. 11. Cluster graph showing landing positions of all saccades (+) (Read and Task sessions included) for R5 reading "The Mummy." Regressions and forward saccades following regressions are not included. The large vertical pile of symbols over the very first letter in the text shows the start position of the initial saccade. The cluster at the beginning of each subsequent line shows the endpoints of the reset saccades. Location 0 on the abscissa is the first character of each line. The shaded bars are the results of the mean shift clustering procedure (see text).

aries. Examples of overlap are: "was pushed" (line 2, R3), "the skull" (line 4, R1), and "Then the" (line 4, R2, R4). Similar trends can be seen for the other 3 texts (Figs. S1–S15).

3.3.3. Summary of local characteristics

The analyses of landing positions in the Repeated Texts showed that saccadic endpoints for a given text and given reader fell into clusters. Clusters could be located at the beginning, middle, or end of words, as well as on or near the spaces separating words. The strength of clustering varied across readers and across the portion of the text being read. Overall, clustering was significantly stronger with Repeated than with Single Texts, showing that clusters could be traced in part to the influence of local text characteristics,

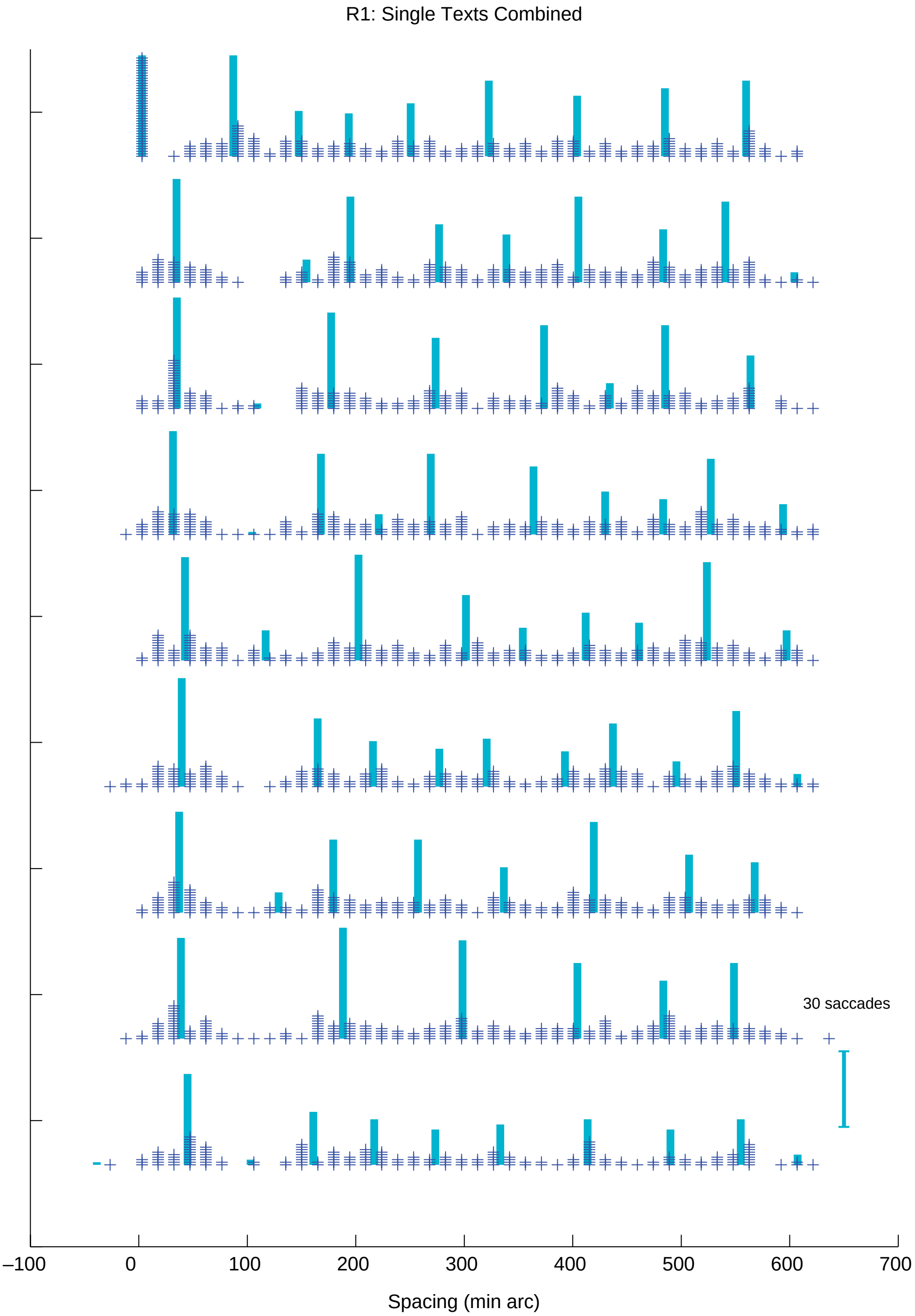

Fig. 12. Cluster graph showing landing positions of all saccades (+) (Read and Task sessions included) for R1's reading of all Single Texts. Regressions and forward saccades following regressions are not included. The large vertical pile of symbols over the very first letter in the text shows the start position of the initial saccade. The cluster at the beginning of each subsequent line shows the endpoints of the reset saccades. Location 0 on the abscissa is the first character of each line. The shaded bars are the results of the mean shift clustering procedure (see text).

and not to tendencies to make saccades of the same average size.

4. Discussion

We measured eye movements of 5 people who read the same 4 texts more than 40 times each. To encourage continued attentiveness to the texts in the face of the repetition, the same text was presented only 4 times in a given day and never on consecutive trials. In addition, comprehension tests were given after each experimental session, and in some experimental sessions a secondary task (detecting occasional changes to the text) was added. Reading of the Repeated Texts was compared to reading of interspersed Single Texts, which were each read only once. Studying reading of the same text many times provides an opportunity to evaluate

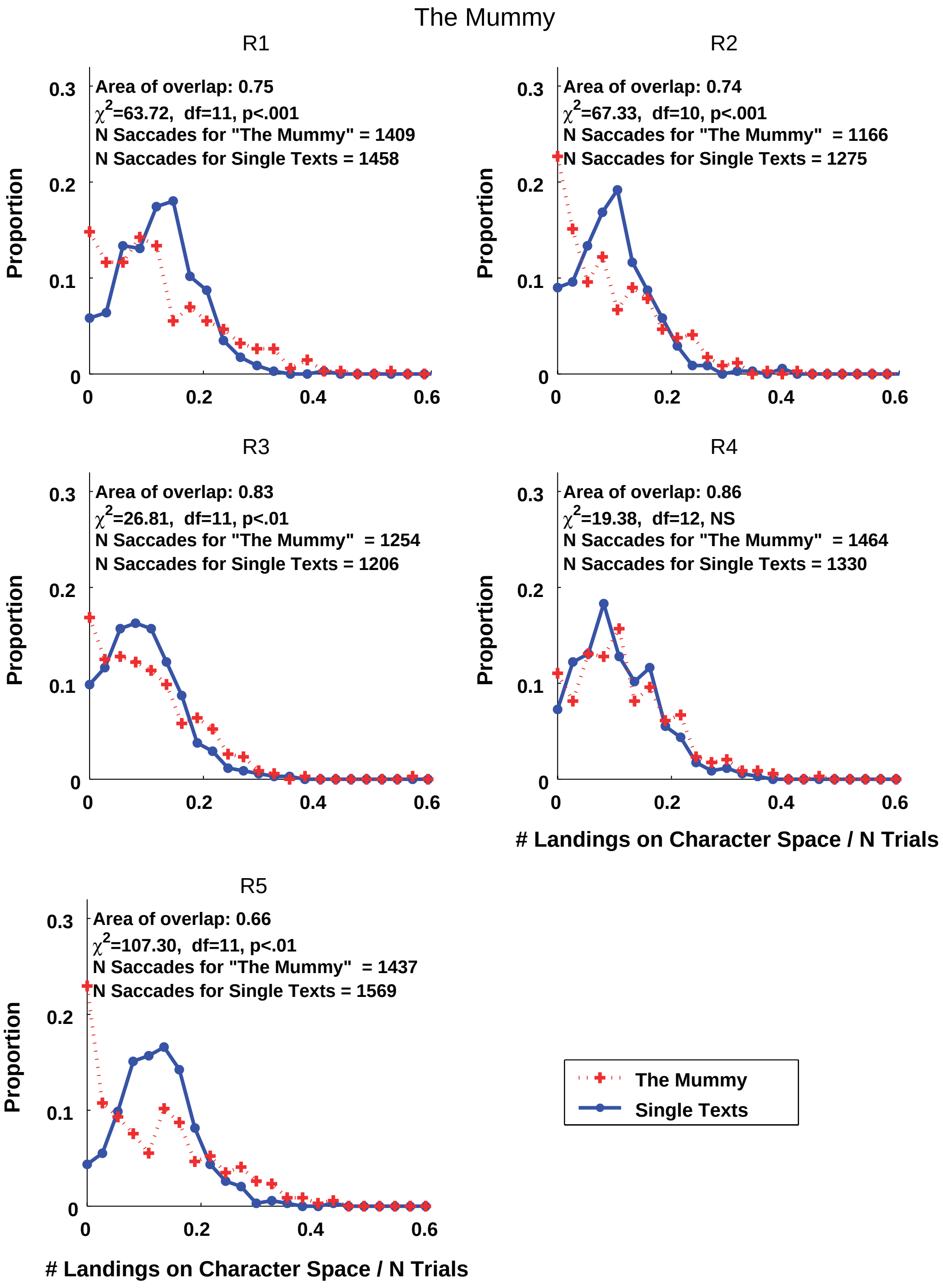

Fig. 13. Proportion of different landing frequencies for “The Mummy” (dotted) and for all Single Texts (solid). The frequency of landing at any given character location (abscissa) was found by dividing the number of landings on a given character location by the number of trials in which the text was read (N). The ordinate shows the proportion of occurrences of different frequency values. Data for the rightmost tails (frequencies >~.3) were pooled when the number of data points per bin was <10. Repeated Text and Single Text distributions were based on 34–38 trials per reader.

the consistency of landing positions within a text in the same reader, and to evaluate characteristics of reading eye movements when the content of the passages is highly familiar and cognitive load is reduced. The discussion below focuses, first, on the global properties of saccades during repeated reading, and then on the significance of the local clustering of landing positions.

4.1. The most consistent effect of repeated reading on global properties of saccades was to reduce the proportion of regressions

All our readers made fewer regressions when reading Repeated Texts, with the proportion of regressions decreasing by 20–50%. In contrast to the reduction in regressions found in all readers, only 3 of the 5 showed changes in forward saccades during reading of repeated text. The magnitude of the changes in forward saccades was modest (<1 character in size and <25 ms in intersaccadic pause duration; Fig. 2 and Table 1). The small changes are in line with prior studies of repeated reading with 2–4 repetitions (Hyönä & Niemi, 1990; Raney & Rayner, 1995) and with studies of the effect of repetition on lexical decision tasks (Balota & Spieler, 1999; Ratcliff, McKoon, & Gomez, 2004). The reader who showed the largest changes in forward saccades with repetition, R2, did so at the cost of reading accuracy, as was shown by R2's low scores (compared to the other readers) on the change-detection task.

The decrease in the frequency of regressions found during repeated reading could have been due to improved accuracy of forward saccades. If this were the case, then the reduction in regressions with repetition would have been restricted to the smaller (1–2 character) "corrective" saccades. This did not occur. Most regressions were larger than 2 characters, and their sizes did not change much with repetition (Fig. 4). The exception was R4, whose regressions became reliably smaller with repeated texts, opposite to the prediction of the error-correction hypothesis. Thus, it is likely that regressions became less frequent with repetition because the increased certainty about the content of the text made it less necessary to revisit previously-seen material.

4.2. The reduction in regression rate with Repeated Texts shows that strategies of saccadic planning during reading favor regressions over a slower pace of forward saccades

The lack of substantial changes to forward saccades during repeated reading implies that the first time a text is read, saccades are already about as large, and are issued about as quickly, as can reasonably be expected on the basis of visual, perceptual and motor limits. Reading a text over and over does little to alter these limits, which are imposed by, for example, acuity, crowding, the speed of visual processing or the speed of saccadic programming. Significant modifications to these processes would have produced more striking changes to forward saccades.

Repeated reading also had little influence on reading strategies, at least in terms of forward saccades. For example, readers could have elected to increase saccade size by relying more on their memory for content than on the immediate processing of the text. They did not, and there are plausible reasons for such a preference. First, it may be difficult for individuals to depart from their typical reading patterns (Vitu et al., 1995). This possibility has some support from our finding that readers maintained their signature saccadic characteristics throughout all the experimental conditions. Second, excessive reliance on memory is risky because memory can be inaccurate, or difficult to access during scanning. Prior work with a variety of tasks has shown that people tend to avoid memory-based strategies for guiding saccades (Ballard, Hayhoe, & Pelz, 1995; Epelboim & Suppes, 2001; Melcher & Kowler, 2001; O'Regan, 1992).

Although repeated reading did not produce either large changes in the pattern of forward saccades, or changes that were consistent across readers, it did reduce the proportion of regressions in all our readers. This suggests that repetition reduced some of the uncertainty about the content of the currently fixated text. Reduction in uncertainty as a result of repetition is not, in itself, surprising. But it does raise interesting issues about the strategies used the first time a given text is read.

Readers could, presumably, reduce the need for at least some of their regressions when reading a text for the first time if they slowed the pace of forward saccades. This option seems, on the face of it, to be efficient because it requires programming of fewer saccades. But programming additional saccades may actually be less costly than increasing the duration of fixation pauses. In visual tasks other than reading, where slowing the pace of saccades would lead to more useful choices about where to look, people instead prefer to scan at a brisk pace, with frequent corrections for glances at useless locations (Araujo, Kowler, & Pavel, 2001; Hooge & Erklens, 1999). Similar strategies have been observed in visual memory tasks (Melcher & Kowler, 2001), in problem solving (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Suppes, Cohen, Laddaga, Anliker, & Floyd, 1983) as well as in studies of reading using text that is changed across fixations (Yang & McConkie, 2001). A strategy of favoring a brisk, but consistent, pace of saccades is also compatible with characteristics of saccadic mechanisms, which have built-in circuitry to set global saccade rates (Dorris, Pare, & Munoz, 1997; Hanes & Schall, 1996; Sparks, Rohrer, & Zhang, 2000), as well as the ability to rapidly program saccadic sequences and, when needed, saccadic corrections (McPeek, Skavenski, & Nakayama, 2000; Zingale & Kowler, 1987). Given these characteristics, it may be more efficient to scan relatively quickly, or at least at a relatively uniform pace, and use additional saccades, as needed, to correct for occasional useless glances, or to compensate for saccades that might leave a region too soon. This is not to say that readers cannot prolong intersaccadic pauses under various circumstances, but rather that they under-utilize this option. Regressions may be more efficient.

4.3. Saccadic landing positions form pronounced clusters

We found significant clustering of saccadic landing positions with repeated texts. The degree of clustering was greater than that obtained with the aggregate of single texts, showing that clustering did not result from tendencies to make forward saccades of approximately the same size. In addition, inspection of the cluster locations showed clusters in various places with respect to word boundaries, including across the space between words. This suggests that clusters did not result from a strategy of aiming saccades to the center of words.

The observed locations of the clusters, however, could have resulted from a mixture of the two strategies, that is, make a saccade to the center of words, and make saccades of approximately the same size. Support for such a mixture of strategies comes from McConkie et al.'s (1988) analysis of saccadic landing positions. They found that landing positions within words could be predicted by two factors: a tendency to direct saccades to the center of the next word, and a tendency to make saccades of about the same size, with both of these factors contributing about equally. This model has been found to account for global characteristics of landing positions, such as the average landing position within words, and the dependence of average landing position within a word on the launch position. Variations of this model have been implemented by others (Reichle et al., 2003; Reilly & O'Regan, 1998), and ideal observer models of saccadic planning, in which saccades are planned so as to optimize word recognition, are able to predict these same global saccadic characteristics (Legge et al., 2002).

We used McConkie et al.'s model to simulate landing positions of saccades over 35 readings of "The Mummy" to find out what kind of cluster patterns it would produce. In the simulation, the length of each saccade was set to the weighted mean of two random variables: (1) a saccade length drawn from a distribution with mean L and standard deviation kL, and (2) a saccade length drawn from a distribution whose mean was equal to D, the distance between the currently fixated letter and the center of the next word, and standard deviation kD. Weights were set to .5, in keeping with McConkie et al.'s findings that both the tendency to look at the center of a word and the tendency to make saccades of approximately the same size contributed about equally. Regressions were not included. The first landing position in each line of text was set to approximate the first landing positions observed in the cluster graphs (Figs. 7–11) (mean landing letter set to 3.5 characters from the start of the line, $SD = 1$ character). The value of the parameters L and k were kept constant across the 35 simulated readings of "The Mummy," and the choice of the values is discussed below. The parameter D was determined for each saccade, and was equal to the distance between the launch position of the saccade and the center of the next word in the line of text.

Initial simulations were performed with the goal of reproducing key features of the readers' forward saccades, namely: the mean size of forward saccades (see Table 1 for individual readers' values) and the strength and pattern of clustering, as shown in Figs. 7–11, and summarized in Fig. 13. We found that setting the mean of the length distribution, L, to 8.2 characters, and the standard deviation parameter, k, to .2 produced a very good approximation to the reading patterns of two of our readers, R1 and R5. Specifically, the mean size of forward saccades produced by the model was 7.4 characters (compare to R1's mean = 7.4 characters, R5's mean = 7.3 characters; see "The Mummy" in Table 1). The simulation also produced clusters similar to those of R1 and R5, as shown in Fig. 14, with clusters appearing at various places with respect to word boundaries (although not always at the same places as observed for the readers; see Figs. 7 and 11). Analysis of the strength of clustering, by means of histograms of the proportion of different landing frequencies (as in 13), showed that the strength of clustering was similar for the model and for these two readers (Figs. 15A and B). The main difference was that R5 showed a tighter pattern of clustering (i.e., more character locations receiving no fixations) than the model. The model's clustering could be made more like R5's by reducing the standard deviation parameter, k (Fig. 15C) although significant differences remained. It is interesting that this straightforward model could produce such a reasonable approximation to the readers' saccadic patterns, with no additional assumptions needed to account for the occurrence or the strength of clustering.

Although the simulation produced patterns of clusters similar to those of R1 and R5, and similar mean saccade sizes as well, the variability of the sizes of the readers' saccades was greater than that of the model's saccades (model $SD = 1.7$; R1's $SD = 2.1$; R5's $SD = 3.2$; see "The Mummy," Table 1). We could increase the variability of the model's saccades by increasing the standard deviation parameter, k, but increasing the value of k resulted in weaker clustering (see Figs. 15D and E, where $k = .3$ and the SD of the model's saccades = 2.0). The same pattern of results was obtained when we used the model to simulate the saccades of the other readers (R2, R3, and R4, where the only difference in the attempts to simulate their data was that a larger value of L was needed). Others have pointed out that the simple mixed strategy model does not account for all the variability of saccades (Reilly & O'Regan, 1998). The important new finding here is that the mixed strategy model underestimated overall saccadic variability while at the same time accounting for the strength of clustering. This outcome suggests that the additional variability of the reader's saccades comes from variability in the locations of the clusters themselves, not from variability of landing positions within clusters.

We doubt that the additional variability of cluster locations was due purely to oculomotor factors. Saccades directed to selected objects, or to sequences of objects, are accurate and variability is low (SD's <10% of saccade size; Gersch, Kowler, & Dosher, 2004; McGowan, Kowler, Sharma, & Chubb, 1998; Melcher & Kowler, 1999; Vishwanath & Kowler, 2003, 2004). Systematic saccadic errors, such as undershooting, or "range effects," are found when saccades are made to follow unpredictable motions of a target (Kapoula, 1985), and are not likely to be relevant to reading (Kowler & Blaser, 1995;Lemij & Collewijn, 1989; Vitu, 1991).

It is more likely that the additional variability in the locations of the clusters is derived from factors related to the selection of the goal region of the saccade. Whether these factors depend on structural properties of the text, such as word length (Reilly & O'Regan, 1998), or strategies related to the ongoing visual processing of fixated words

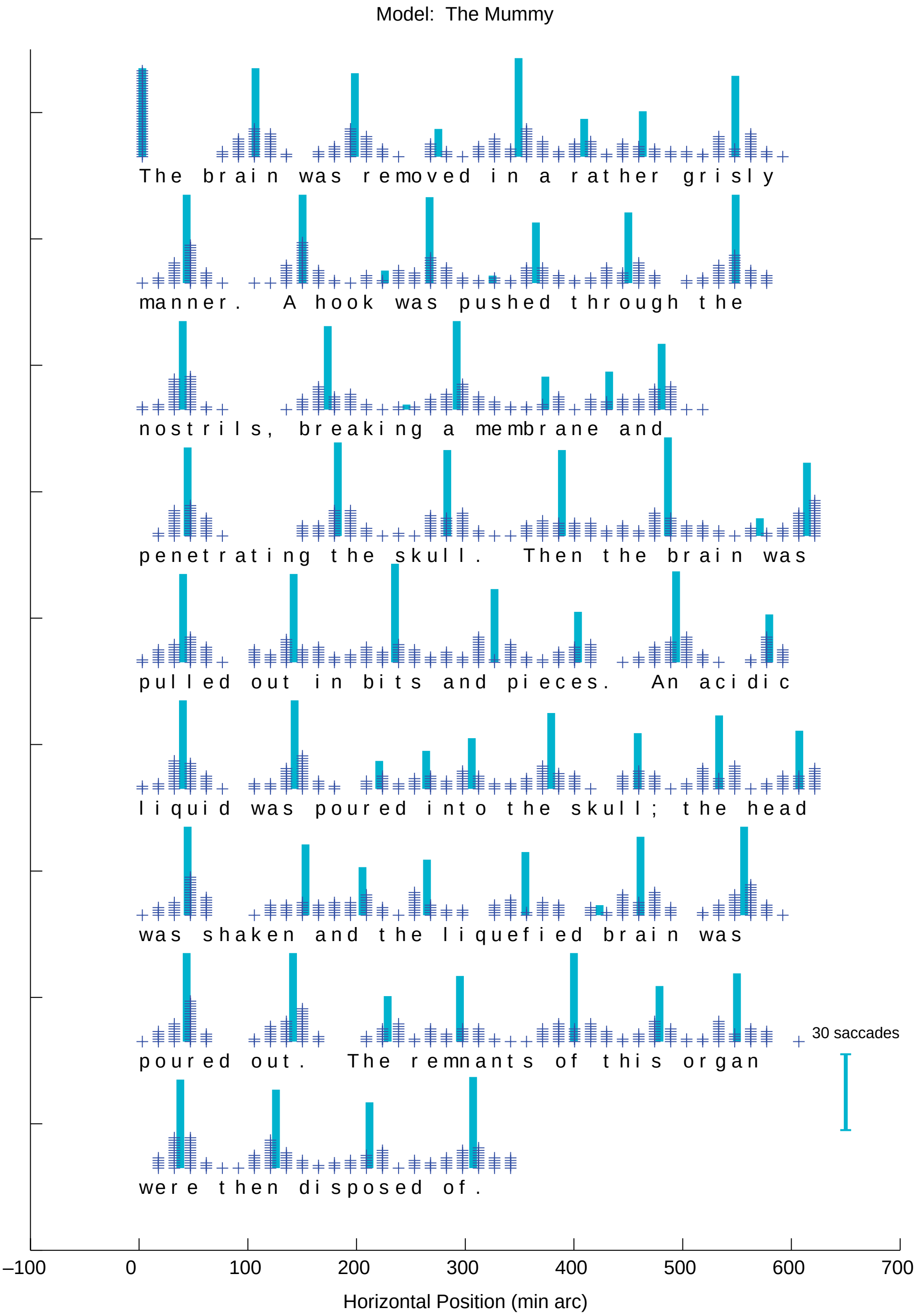

Fig. 14. Simulation of landing positions of forward saccades (+) produced by the mixture model (see text) reading "The Mummy" 35 times. Parameter values: $L = 8.2$ characters; $k = .2$. The shaded bars are the results of the mean shift clustering procedure (see text).

(Epelboim et al., 1994, Epelboim, Booth, & Steinman, 1996; Kowler & Anton, 1987; Legge et al., 1997), cannot be determined from our results. These issues, however, can be addressed by further studies of repeated reading with texts chosen on the basis of their structural, syntactic or semantic characteristics. Our findings of reliable clustering of saccadic landing sites, combined with the modest changes to the global characteristics of saccades during repeated reading, provide reasons to be optimistic that further application of this technique will provide useful insights about strategies of saccadic control. Multiple observations on single individuals have been a mainstay of psychophysical research. The same may prove to be true of reading.

4.4. Summary of main findings and conclusions

1. Global characteristics of saccades across multiple readings of the same text were quite similar to global charac-

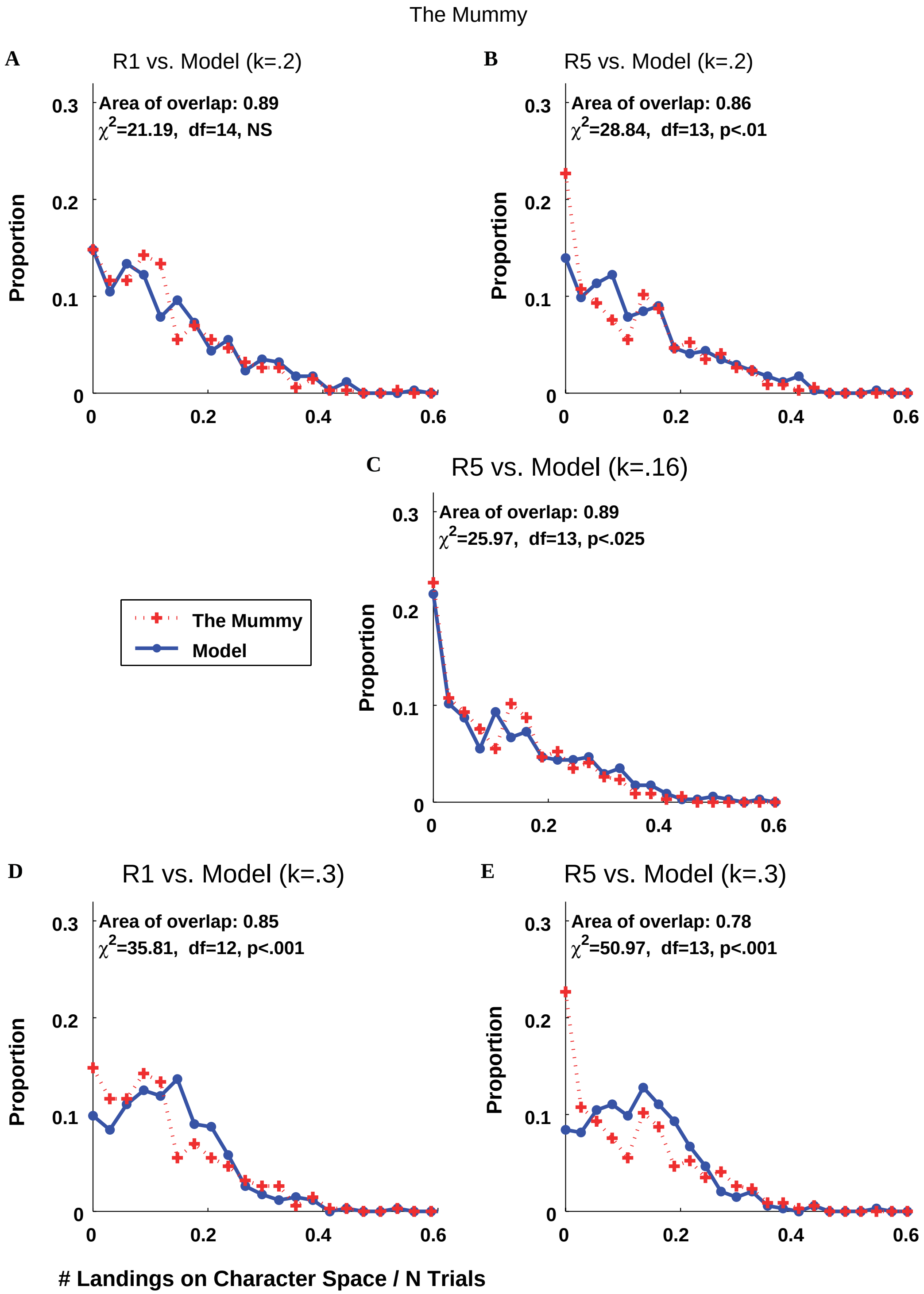

Fig. 15. (A–E) Proportion of different landing frequencies for "The Mummy" for R1 and R5 (dotted) reproduced from Fig. 13, and by the mixture model (solid). Model parameters: $L = 8.2$ characters; $k = .2$ (A and B), .16 (C) or .3 (D and E). The frequency of landing at any given character location (abscissa) was found by dividing the number of landings on a given character location by the number of trials in which the text was read (N). The ordinate shows the proportion of occurrences of different frequency values. Data for the rightmost tails (frequencies >~.3) were pooled when the number of data points per bin was less than 10. Each histogram is based on 1400–1700 saccades.

teristics during single readings of different texts. These characteristics include the average size of forward saccades, average pause duration and average landing position within words. The most consistent effect of repetition was to reduce the proportion of regressions. This implies that memory for the content of the text acquired through repetition does not substantially accelerate word recognition or saccadic planning, and that readers may prefer to cope with uncertainty about text content or meaning the first time they read a text by using regressions, rather than by slowing the pace of forward saccades.

2. Saccadic landing positions fell into clusters that were located at a variety of places with respect to word boundaries—the beginning, middle or end of words, or across word boundaries. The strength of clustering could be accounted for by a mixture model in which saccade length depends on two, equally-weighted, global strategies: aim to the center of the next word, and restrict the size of saccades to about the same value throughout. This simple mixture model, however, could not account fully for the locations of the clusters, pointing to a role for other features of the text in guiding saccades. The reliable clustering of saccadic landing positions found during multiple readings of the same text opens the way for cluster patterns to be used to study eye movement strategies during reading and overcome at least some of the variability associated with traditional global single-text measures.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2005.09.023.

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