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Eye-movement control during learning and scanning of Landolt-C stimuli: Exposure frequency effects and spacing effects in a visual search task

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Abstract

We examined whether typical frequency effects observed in normal reading would also occur in a target search task using non-linguistic Landolt-C stimuli. In an initial learning session, we simulated development of frequency effects by controlling exposures participants received of Landolt-C clusters during learning. In a subsequent scanning session, we manipulated the cluster demarcation form of linear strings of Landolt-C clusters (i.e., spaced vs. unspaced vs. shaded unspaced). Participants were required to scan and search for pre-learnt target clusters that were embedded in longer Landolt-C strings. During learning, frequency effects were successfully simulated such that targets with more exposures received shorter fixation time than those with fewer exposures. Participants were unable to successfully detect the pre-learnt targets when they were embedded in the strings during scanning. No evidence of frequency effects was observed in the scanning session. In contrast, eye-movement control was significantly influenced by cluster demarcation form, with increased difficulty for unspaced strings, less for shaded strings, and least for spaced strings. Furthermore, typical landing position distributions that occur in reading of spaced languages also occurred during scanning of spaced Landolt-C strings but not for the shaded or the unspaced strings. In conclusion, exposure frequency effects were successfully simulated during learning but did not carry over to target search during scanning of Landolt-C strings. Possible reasons why frequency effects did not occur in the scanning session are discussed.

Keywords Landolt-C · Exposure frequency · Cluster demarcation · Visual search

Introduction

In the current study, we are interested to examine how exposure frequency qualifies the rate at which abstract visual stimuli (Landolt-C clusters) are learnt cumulatively based on repeated exposures. Eye-tracking methodology has been widely used to examine a variety of domains of human cognitive processing (e.g., reading, visual search, scene perception) because eye-movement data provide an excellent index of moment-to-moment cognitive processing (see Rayner, 1998). Eye-movement data have been demonstrated to be very informative in revealing the nature of on-line processing during reading. However, what factors drive when and where to move the eyes in reading is still controversial (Radach & Kennedy, 2013; Murray et al., 2013; Rayner, 2009; Starr & Rayner, 2001).

Despite the clarity that exists regarding frequency effects during reading in the literature (e.g., Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see also Liversedge et al., 2004), it remains controversial as to whether frequency effects exist for tasks that, arguably, do not involve natural written language processing, such as mindless reading, visual search in text, and proofreading (cf., Kaakinen & Hyönä, 2010; Rayner & Fischer, 1996; Rayner & Raney, 1996; Vanyukov et al., 2012; Vitu et al., 1995). Rayner and Raney (1996) demonstrated that typical word frequency effects occurred during normal-text reading but did not occur during target word search within texts. Similar results were reported by Rayner and Fischer (1996), where they showed that word frequency affected fixation durations in normal reading but did not affect fixation durations when the task required searching for a target word in

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normal text. A more recent study conducted in the context of Chinese reading also reported a lack of word frequency effects in a task where participants were required to search for a specific target within Chinese texts (Wang et al., 2019). Thus, it has been argued that eye-movement control operates according to quite different principles during normal reading and visual search, such that the determinants of when to move the eyes vary as a function of task demands (Rayner, 1995; Rayner & Fischer, 1996; Rayner & Raney, 1996; see also Vitu et al., 1995, for a different view). Most studies investigating, but failing to obtain robust word frequency effects in target search tasks, involved search through normal texts. However, Vanyukov et al. (2012) examined a similar theoretical question by using Landolt-C stimuli in a task in which participants were required to detect a target O. Interestingly, the frequency effects that failed to appear in the visual search in normal text employed by Rayner and colleagues did emerge in the Landolt-C scanning experiment reported by Vanyukov et al. Vanyukov et al. found that non-target Landolt-C clusters that were presented as distractors more frequently received shorter fixation durations than those presented less frequently. Vanyukov et al. argued that the more frequent the exposures to the distractor Landolt-C clusters, the more robust would be the representations for those clusters in memory, and this in turn would contribute to their easier access from memory. It should be apparent that it is currently unclear as to the precise experimental circumstances that are required in order for frequency effects to occur in a target search task. Based on existing studies, sometimes frequency effects emerge, and sometimes they fail to emerge.

One motivation of the current study was to better understand what is driving frequency effects in target search during the scanning of normal text, and Landolt-C strings (Rayner & Fischer, 1996; Rayner & Raney, 1996; Vanyukov et al., 2012; Wang et al., 2019). According to processing models of eye-movement control, the trigger of when to move the eyes differs across visual search and reading in that these two tasks impose different cognitive processing demands (Rayner, 1995; Rayner & Raney, 1996; Reichle et al., 2008; Reichle et al., 2012). During reading for comprehension, high-frequency words are accessed faster than low-frequency words during lexical identification. Consequently, high-frequency words receive shorter and fewer fixations compared with low-frequency words. Also, high-frequency words are more likely to be skipped during first-pass reading compared to low-frequency words. However, during visual search for a target word, it is less clear whether lexical access is, or is not, initiated. If lexical access did occur, one would anticipate that high-frequency words would receive shorter fixations than low-frequency words during visual search. And note that such frequency effects might also occur in respect of abstract orthographic memory representations for non-linguistic stimuli such as the Landolt-C strings employed by Vanyukov et al. (2012). In contrast, if lexical access was not necessary in the task, one might anticipate no word-frequency effects, as was the case, for example, during the target word search tasks in Rayner and Raney (1996) and Rayner and Fischer (1996). Thus, whether frequency effects do, or do not, emerge for target words in visual search seems to depend on whether lexical access is, or is not, initiated. In the current study, we required participants to search for a target Landolt-C cluster that was embedded in a horizontally extended linear array of Landolt-C clusters. Unlike previous studies in which participants were required to search for a specific word, in this study, the targets to be detected during search were formed from a set of Landolt-C clusters that had previously been learnt during a learning session. Importantly, the frequency with which clusters were presented during learning – that is, the exposure frequency – was manipulated during the learning session. We assumed that in the present task, if participants were to complete the visual search task successfully, it would be necessary for them to access representations of target Landolt-C clusters that had been instantiated and stored in memory based on exposures to those clusters during the learning phase of the experiment. If accessing a representation of a Landolt-C cluster stored in memory is akin to accessing a stored representation of an orthographic string associated with a word, then it is quite possible that we might observe frequency effects during our Landolt-C target cluster search task.

Another important characteristic of previous studies that have investigated word frequency effects in visual search is that the stimuli have always been presented in normal word-spaced English texts (Rayner & Fischer, 1996; Rayner & Raney, 1996), or in horizontally extended Landolt-C strings in which spaces appeared between individual clusters giving search arrays a sentence-like appearance (Vanyukov et al., 2012). However, the presence of spaces between words or clusters in these visual search tasks might affect the emergence of any potential frequency effects. That is to say, the presence of word spacing could potentially ease the difficulty of searching for a target string (through reduction of lateral masking and crowding, and due to demarcation of the target as a distinct visual cluster), making it a relatively simple process. It was for this reason that in the present experiment we also manipulated the cluster demarcation forms of our Landolt-C strings with respect to the individual clusters comprising them.

In the current study, we modified a Landolt-C paradigm adopted by Williams and Pollatsek (2007), in which participants were asked to search for a target O embedded in a single Landolt-C cluster (e.g., ), or alternatively in a linear sequence of Landolt-C clusters (e.g., ). Additionally, Williams and Pollatsek manipulated the size of the gap in the Landolt-C rings (small or large). They found that eye movements were sensitive to gap size, showing immediate disruption to processing, that is, longer fixation times for smaller than larger gaps during search. In our study, we extended the target word search experiments reported by Rayner and Raney (1996) and Rayner and Fischer (1996) as well as the target O search during scanning of Landolt-C strings by Vanyukov et al. (2012) by manipulating (1) the exposure frequency of Landolt-C clusters during cumulative learning, and (2) the form of the Landolt-C cluster demarcation during target Landolt-C search. In the first session of the current experiment, participants learnt target Landolt-C clusters. During the learning session of the experiment, we manipulated the exposure frequency of the targets. For high-frequency targets, each cluster was encountered four times, whilst for the low-frequency targets, each cluster was encountered just once. Learning accumulated over five learning blocks, giving an accumulated exposure frequency for high-frequency targets of 20 presentations in contrast to an accumulated exposure frequency for low frequency targets of just five presentations. We used Landolt-C rings with a constant gap size, but we varied the gap orientations to create distinctive three-C clusters (e.g., ). After learning the target Landolt-C clusters, participants then scanned through extended horizontal arrays of Landolt-C clusters that were nine clusters long (i.e., Landolt-C strings). Target Landolt-C clusters were either present (50% of trials) or absent. Participants were required to determine whether a target Landolt-C cluster that they had just learnt was present in each Landolt-C string. The Landolt-C strings were presented to participants in three cluster demarcation forms: (1) with spaces between each individual Landolt-C cluster; (2) with no spaces, but with shading to demarcate cluster boundaries; (3) without spaces in an unspaced format (e.g., spaced strings, shadedstrings, unspacedstrings, respectively).

Using our Landolt-C learning and scanning paradigm, we first wished to simulate an exposure frequency effect during the learning of target Landolt-C clusters. The idea that humans are able to learn nonsensical visual stimuli after only a small number of exposures dates back to Ebbinghaus (1885). However, in the present study, we were mainly interested in how the degree of stimulus exposure would affect the rate of learning, and how the magnitude of any exposure frequency effect would develop across learning blocks. Our basic prediction was that the more exposures of a stimulus that a participant receives, the more robust the corresponding representation instantiated and stored in memory (cf., Reichle & Perfetti, 2003; Vanyukov et al., 2012). Therefore, in the current study, we predicted that four exposures in each learning block would accelerate learning compared to a single exposure per learning block. Beyond this prediction, we also considered the discrepancy between the learning curves for the high- and low-frequency target clusters. In our experimental design, the amount of exposure to a high-frequency string relative to a low-frequency string is constant in each block such that the ratio remains 4 to 1, respectively. Thus, if the rate of learning proceeds according to rate of exposure per learning block, then learning should be constant, that is, there should be main effects of learning block and main effects of exposure frequency, but no interactive relation between the two. Alternatively, if the rate of learning is cumulative (regardless of the fact that exposure across blocks is constant), then the relationship between learning block and exposure should be multiplicative, that is to say, there should be an interactive relation between the two.

Finally, as described above, we also manipulated cluster demarcations during the scanning of Landolt-C strings. Our spaced, shaded, and unspaced formats allowed us to directly examine whether the presence of spacing information provides increased facilitation in accessing the representations of learnt stimuli from memory in visual search to a greater degree than demarcations that provide visually explicit cluster boundary information but no reduced lateral masking or crowding. Therefore, we anticipated that if spaces do benefit Landolt-C target search more than alternating shadings, then we would observe shorter search times in spaced strings relative to shaded strings. Such a result would suggest both cluster boundary demarcation and lateral masking and crowding affect cluster recognition in visual search. Alternatively, if cluster boundary demarcation is sufficient to permit effective target search, then eye movements would be comparable for cluster spaced and shaded conditions relative to the unspaced unshaded condition. If this was the case, we would see comparable search times in both spaced strings and shaded strings, but longer search times in unspaced unshaded strings. If the memory for target clusters acquired in the learning session maintains through to the scanning session, we should see longer processing time on low-frequency targets relative to high-frequency targets. Furthermore, such an exposure frequency effect would be larger in the unspaced strings compared to spaced and shaded strings.

Method

Participants

A power analysis using the PANGEA power application (Westfall, 2015) was conducted on the interaction effects between exposure frequency and spacing format, and the results indicated the minimum sample size for the current study was 15 to obtain 80% prior chance of finding a medium effect size (d = 0.5, Cohen, 1962). We recruited 24 participants with normal or corrected-to-normal vision from the University of Southampton to take part in our experiment. All of them were native speakers of spaced alphabetic languages. They gained 36 course credits or £18 for participating.

Apparatus

The experiments were run using a 20-in. CRT monitor with a refresh rate of 60 Hz. Stimuli were displayed on a white-background screen with a resolution of 1,280 × 1,024 pixels. Participants were seated 70 cm from the monitor, and at this viewing distance one Landolt-C ring extended to approximately 0.76° of visual angle (each Landolt-C was 30 × 30 pixels). A chin and forehead rest were used to minimise participants' head movements. Participants' eye movements during both the learning session and the reading session were tracked using an SR Research Eyelink 1000 system with a sample rate of 1,000 Hz. Viewing was binocular, but only the position of the right eye was recorded.

Materials

Landolt-C stimuli were used in the current study. A Landolt-C ring is a C-ring in which the gap could vary in size and orientation. In this study, we fixed the gap size of Landolt-C ring to be 6 pixels wide and created eight unique Landolt-C rings by rotating the orientation of the gap angularly equidistantly. The Landolt-C rings were then used to compose three-ring clusters (see Fig. 1). In total, 504 unique clusters were constructed. Twenty-eight clusters that each contained three different rings were selected as target clusters. These target clusters were to be learnt in the first session of the experiment.

We constructed horizontal Landolt-C frames into which to insert the target clusters. To do this we shuffled all the clusters to construct extended horizontal strings of Landolt-C clusters.[1] In total, 56 frames of Landolt-C strings that each contained nine clusters were constructed. Half of these Landolt-C strings contained a target cluster positioned in the second to the eighth cluster position in the string (see Fig. 2). The same frames of Landolt-C strings were used across three cluster demarcation forms (i.e., spaced strings; shadedstrings; unspaced strings). In the spaced strings, there was a 30-pixel gap between adjacent Landolt-C clusters. In the shaded condition, adjacent Landolt-C clusters were demarcated by shading (e.g., black and grey shadings). In the unspaced condition, no visual cluster demarcations were present. The displayed sentences occupied 862 pixels (22° of visual angle) and 1,086 pixels (27° of visual angle) for unspaced/shaded condition and spaced condition, respectively.

[1] To avoid overlapping ambiguity appearing in successive clusters when visual cluster demarcations were absent, we ensured our Landolt-C clusters met the followed criteria: (1) the final C of cluster n was different from the beginning C of cluster $n+1$; (2) in target present trials, each Landolt-C ring was unique within the target cluster, meaning the 8 distractors had no similar C elements to the target; (3) in all trials, it was ensured that all the potential clusters produced due to incorrect segmentation were different from target clusters.

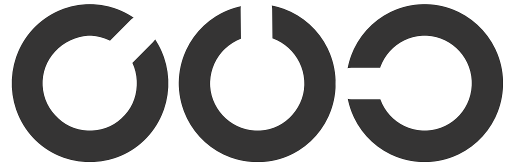

Fig. 1 An example of a Landolt-C cluster. The gap size of each Landolt-C ring was 6 pixels. Each Landolt-C ring occupied 30 pixels. There were eight possible gap orientations, each of which was equi-rotated through 360° (e.g., 0°, 45°, 90°, 135°, etc).

Experimental design

There were two sessions in the current experiment: an initial learning session and a subsequent scanning session. In the learning session, participants learnt target clusters displayed in isolation. During learning, we manipulated the exposure frequency of target clusters, that is, 14 targets were presented four times per learning block, whilst the other 14 targets were presented just one time per block. This accumulated to 20 exposures for high-frequency clusters and five exposures for low-frequency clusters in total over five learning blocks. We rotated exposure frequency of targets across participants and stimuli. After the first, third and fifth learning block, a learning assessment task took place to evaluate the degree to which participants had learnt the targets. They had to decide whether a Landolt-C cluster was one of those they had learnt in the learning blocks. In each learning assessment, 50% of the trials displayed a target cluster. The other half of trials contained a distractor. Each distractor used in the learning assessment task was unique (and we used different distractor sets in each learning assessment). Like our target clusters, distractors that appeared in the learning assessments were also comprised of three Landolt-C rings; however, we ensured that these had a significant degree of dissimilarity in respect of the constituent C orientations. Thus, the visual complexity of the targets and distractors was the same. In addition, we controlled the degree of overlap between targets and distractors appearing in the learning assessments to ensure that this was very low. To quantify the degree of overlap between targets and distractors, we adopted a metric such that if a Landolt-C target cluster and a Landolt-C distractor cluster shared a C in the same orientation in the same respective position within the cluster (position 1, or position 2, or position 3), then the overlap was 33%. The mean degree of overlap between all the distractor and target clusters was 27%, meaning that, on average, targets shared less than one C in the same orientation in the same position across all the distractors. Thus, there was a low level of shared overlap. Based on our efforts to not repeat distractors during learning, and to minimise overlap between targets and distractors, we consider that it is likely that participants relied on memory representations of specific stimuli formed during learning to identify targets rather than ad hoc strategies to discriminate targets from distractors.

Fig. 2 Example of Landolt-C strings presented in the three cluster demarcation forms. There might be a target cluster embedded in the string at the second to the eighth cluster position

In the scanning session, participants were required to scan extended Landolt-C strings and determine whether a target cluster that they had learnt in the learning session was, or was not, present. During scanning, we manipulated the cluster demarcation form of the Landolt-C strings. Strings with the same cluster demarcation form were presented in the same block and there were three blocks. Target frequency was presented intermixed in each block. Cluster demarcation form was counterbalanced across scanning blocks following a Latin Square design. Trial orders in both learning session and scanning were randomized.

Procedure

Before each learning session block, a nine-point calibration was performed until the mean error was less than 0.5°. Before each scanning block, a three-point calibration was performed until the mean error was less than 0.2°. Recalibration was carried out if tracker loss occurred or after each break. During both sessions, we tracked eye movements.

In the learning session, each learning trial began with a box appearing slightly left of the centre of the display. Once participants fixated the box, the cluster appeared centrally on the screen, and a square box appeared simultaneously to its right. The box presented to the right could appear at one of four positions at different points on the same vertical line. Participants were required to learn the cluster displayed on the screen and once they felt they remembered the cluster they moved their eyes to the square box on the right side of the screen to terminate the trial. The learning assessment task occurred after the first, the third and the fifth learning blocks. In each learning assessment trial, participants initiated the trial by fixating a box slightly left to the centre and terminated the trial by pressing a button to indicate whether they had learnt the displayed cluster.

After the learning session, participants were instructed to perform target detection tasks during the scanning of Landolt-C strings. Each trial started with a black circle on the left side of the screen (i.e., drift correction). Once participants fixated the black circle, the Landolt-C string appeared. Participants scanned along the string from left to right to detect whether a target cluster was present. After they had determined whether a learnt target cluster was, or was not, present, they pressed a button terminating the display and causing a question to appear asking the participant whether they had, or had not, detected a cluster they learnt in the learning session.[2] Participants responded by pressing a button to indicate either a 'Yes' or a 'No' response.

During the two sessions, participants had short breaks whenever they wanted. In total, the experiment took approximately 3 h to complete.

Data analysis

Individual data points that were more than ±3 standard deviations from the overall mean for each dependent measure were removed. In the learning session, 0.9% of data were missing due to tracker loss and 2.4% of data (averaged across different measures) were removed after the trimming procedure. In the scanning session, we removed 44 trials that contained more than 25 blinks in the scanning of the Landolt-C string (1%). For the analysis of global measures (see below), 1.45% of data were trimmed. For the local measures, 6% of trials contained no data on the target cluster, and these were removed from the analysis. For the analysis of local measures (see below), the data on targets for which skipping occurred during first pass scanning were excluded (2.4%), and data beyond ±3 standard deviations from the global mean were also removed (1.1%).

Generally, we examined the following eye-movement measures: (1) first fixation duration (the duration of the first fixation on a cluster word); (2) gaze duration (the sum of fixations on a word before a saccade away from that word); (3) number of fixations in an interest area; (4) total viewing time (the sum of all fixations in a region); (5) incoming saccade length; (6) outgoing saccade length; (7) initial landing position of the eyes in the region of interest; (8) mean fixation duration; (9) mean saccade amplitude (all saccades made during the scanning including both forward saccades and backward saccades; these amplitudes were converted to absolute values for the calculation).

[2] During testing, participants were free to press a button to terminate a trial. In total, 15% of trials were terminated immediately participants detected a target. That is, when a button press occurred during a fixation on the target cluster. Most trials were not terminated until the eyes had moved past the target cluster.

To normalise the distributions, we natural log transformed the reading time variables before running the linear mixed-effects models. This was not necessary for the mean landing position data which were normally distributed, and, therefore, no transformations were applied. To analyse continuous eye-movement measures (e.g., fixation durations), we used linear mixed-effects models (LMMs; see Bates et al., 2016) with a full random-effects structure in the first instance (Barr et al., 2013). That is, using the maximal random effects structure justified by the design. For example, in a model of full random effects structure lmer = lmer(DV ~ Factor1 * Factor2 + (1+ Factor 1 * Factor 2|participant) + (1+ Factor 1 * Factor 2|item), DATA), we included intercepts and slopes for both random factors (i.e., participants and items). When this full (maximal) model failed to converge, we then trimmed the random structure of the model by initially removing the correlations between fixed factors and then interactions and then random factors until the model converged successfully. Trimming procedures started with items and then participants. For binary variables (e.g., accuracy), we used logistic generalized mixed-effects models (GLMMs).

Results

Learning session

In this section, we report eye-movement results from the learning blocks and then report behavioural data and eye-movement results from the learning assessment task.

Learning blocks

First, we assessed the main effect of learning block that we assumed was an index of learning. Second, we examined whether shorter and fewer fixations were made on target clusters that received four exposures per block relative to one exposure per block (i.e., the main effect of exposure frequency). More interestingly, we investigated how the magnitude of exposure frequency effects changed across learning blocks. See Table 1 for the means and standard errors of first fixation duration, total viewing time[3] and fixation numbers on high-frequency and low-frequency clusters from learning block 1 to learning block 5. In our LMMs we set learning block as a numeric factor and built contrasts for frequency using the *contr.sdif* function from MASS package in R environment and then ran the linear mixed-effects models to examine the main effects and the interaction between exposure frequency and learning block (see Tables 1 and 2).[4]

During the learning of target clusters, first fixation durations were not affected by exposure frequency or learning block, nor was there any reliable interactive effect. As predicted, we found main effects of learning block on total viewing time and fixation number. Participants made shorter and fewer fixations in the later learning blocks relative to the initial learning blocks. Importantly, the main effects of learning block were qualified by interactive effects with exposure frequency such that the learning effects were larger for high-frequency exposure than low-frequency exposure (see Figs. 3 and 4 for effect plots).

Learning-assessment tasks

There was a learning-assessment task after the first, third and fifth learning blocks. Participants' mean accuracy increased from 59% in assessment block 1 to 67% in assessment block 3. The false-alarm rate was 18.3% in assessment block 1 and dropped to 16.9% in assessment block 3. The mean hit rate for high-frequency targets reached a level beyond chance in the first block and increased to 75% in the final block. By contrast, mean hit rate for low-frequency targets in the first block was 46% and the mean hit rate in the final block reached 60%. It is clear that our participants were more sensitive to high-frequency targets compared to low-frequency targets (see Table 3).

We built the logistic generalized mixed-effects model to formally examine mean hit rate (see Table 4). Robust exposure frequency effects and block effects were found on mean hit rate. Specifically, hit rate was higher for high-frequency targets relative to low-frequency targets, and mean hit rate also increased across blocks. Numerically, participants took more time to decide whether they had learnt the displayed cluster for low-frequency targets relative to high-frequency targets. A robust block effect on reaction time was obtained indicating that participants responded faster as learning accumulated.

Eye movements in the learning assessment blocks were also examined (see Table 4). Main effects of block were found on total viewing time and fixation number. Consistent with the reaction time results, shorter and fewer fixations were made during the learning-assessment task as block increased.

Scanning session

Despite participants attaining 67% accuracy with respect to target and distractor categorization decisions in the final learning assessment block, the mean accuracy in the scanning session reduced to 54%. False-alarm rate during scanning (Press

[3] During each individual learning trial, participants almost always made a saccade to fixate the cluster, and then remained making fixations on the cluster until they felt confident that they had learnt it, at which point they made a saccade to the box to the right. For this reason, gaze durations were almost always identical to total viewing time on the cluster, and therefore, we only report total viewing time in these analyses.

[4] All the treatments were uniform across the five learning blocks. Moreover, the total time spent learning the clusters accumulated across the blocks. We, therefore, treated block as a continuous variable.

Table 1 Mean first fixation duration (ms), total viewing time (ms) and fixation number on target clusters across the learning blocks

	High frequency					Low frequency				
	LB 1	LB 2	LB 3	LB 4	LB 5	LB 1	LB 2	LB 3	LB 4	LB 5
First fixation duration	373	380	395	402	398	386	357	379	419	404
	(29)	(30)	(32)	(32)	(29)	(59)	(61)	(57)	(63)	(64)
Total viewing time	4453	3529	2724	2665	2361	4760	4228	3663	3618	3316
	(279)	(260)	(203)	(213)	(181)	(466)	(490)	(467)	(451)	(450)
Fixation number	10.4	8.5	6.8	6.7	6.1	11.2	10.0	9.0	8.8	8.3
	(0.6)	(0.6)	(0.5)	(0.5)	(0.4)	(1.3)	(1.1)	(1.1)	(1.1)	(1.1)

Note. LB1 refers to learning block 1. LB 2 refers to learning block 2 and so forth. Standard errors are in parentheses. In each learning block, high-frequency clusters were presented four times each and low-frequency clusters were presented just one time each

'yes' button when no target was present) was 40%. The mean hit rate (accurate detection) across all conditions during scanning was below 50% (see Table 5). Formal GLMMs analysis showed that there was no difference on hit rate across all conditions (see Table 6). These data indicated that during scanning, participants experienced difficulty in discriminating target clusters from non-target clusters. Regardless of the poor detection performance, we analysed the eye-movement data observed on every Landolt-C cluster in the extended horizontal strings as well as the data observed solely for the target clusters.

Analysis of global measures

During scanning of Landolt-C strings, mean fixation duration was shorter in the spaced strings compared with shaded strings and unspaced strings. Also, shorter mean fixation durations occurred for the shaded strings than the unspaced strings (see Tables 5 and 6). Recall that a Landolt-C covered 0.76° of visual angle. Mean saccade amplitude was longest in the scanning of spaced strings (1.6° of visual angle), and somewhat less in the shaded strings (1.3° of visual angle). Mean saccade amplitude was shortest in the scanning of unspaced strings, 1° of visual angle. The saccade amplitude data demonstrate clearly that when scanning unspaced Landolt-C strings, participants moved their eyes on average from one Landolt-C to the next. They did not move their eyes, such that, on average, they fixated one cluster followed by the next. Participants were more likely to make longer saccades (and therefore, saccades between clusters) under the spaced and shaded conditions. Clearly, demarcating clusters by shading or spacing impacted saccadic targeting. Additionally, the largest effect on saccade amplitudes that occurred for the spaced condition was driven, at least in part, by the increased horizontal spatial extent of the Landolt-C strings in this condition. Thus, there were contributions to the saccade amplitude effects from both cluster demarcation and increased spatial extent. Based on all the global measures, it is clear that participants found scanning Landolt-C strings to identify a target most effortful in the unspaced condition (i.e., longer fixation durations, shorter saccade amplitudes), somewhat less effortful in the shaded condition and easiest in the spaced condition.

Analysis of local measures

In the scanning session, hit rate was quite similar between high-frequency targets (49%) and low-frequency targets (45%). This 4% difference on hit rate between high- and

Table 2 Fixed effect estimates from the linear mixed-effects models (LMMs) for first fixation duration, total viewing time and fixation number on target clusters across the learning blocks

	First fixation duration			Total viewing time			Fixation number		
	b	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
Intercept	5.71	0.06	94.71***	8.30	0.11	76.38***	2.23	0.11	19.92***
Frequency	-0.04	0.04	-0.97	0.06	0.04	1.31	0.06	0.04	1.43
Block	0.02	0.01	1.73	-0.13	0.02	-6.42***	-0.10	0.02	-5.33***
Frequency*Block	0.01	0.01	0.80	0.05	0.01	4.07***	0.04	0.01	3.23***

Note. High exposure frequency was treated as the baseline in the LMMs

*** $p < .001$, ** $p < .01$, *$p < .05$

low-frequency clusters was considerably smaller than the 15% difference obtained in the final learning-assessment task. Thus, we have two measures of target cluster recognition that show quite different effects in the same group of participants. We consider it likely that this difference in effects reflects increased difficulty associated with detecting a target cluster embedded within contemporaneously presented strings of distractor clusters. Presumably, the interference from such distractors is substantial and does not occur when non-target clusters are presented non-contemporaneously from trial to trial in the learning-assessment task.

As shown in Table 6, there were no main effects of exposure frequency for any of the fixation time and fixation location measures.[5]

As there is evidence showing that frequency effects can occur when participants are unaware of the repetition of an element in a search display (Chun & Jiang, 1998), it was also possible that in the current study eye-movement measures could show difference between high- and low-frequency strings when participants were not consciously aware of the presence of the target. To be clear, there was at least the possibility of implicit effects. To test this possibility, we split the data based on whether or not participants had successfully detected the target during string scanning. If participants failed in target detection when a target was truly present in the string, we considered that they were unaware of the presence of the target. Alternatively, if participants successfully detected the target that was embedded in the string, we considered that they were consciously aware of the presence of the target. The results of these analyses showed that exposure frequency effects did not occur, regardless of whether participants were aware or unaware of the targets during string scanning. Thus, we found no evidence of implicit effects of frequency during scanning.[6]

By contrast, significant spacing effects occurred for both fixation duration and fixation location measures. Longest fixation durations were observed in the unspaced condition as predicted. Surprisingly, we found longer and more fixations in the spaced condition compared to the shaded condition. However, significantly longer mean fixation durations were observed in the shaded condition than the spaced condition when every individual cluster was included in the analyses. In relation to saccadic behaviour, we found robust spacing effects on incoming saccade length, outgoing saccade length and mean landing position. Incoming saccades were shortest for target clusters in the unspaced condition, somewhat longer for targets in the shaded condition and longest for targets in the spaced condition. Similar effects were obtained for mean landing positions on target clusters and outgoing saccades from target clusters. These results support the claim that spacing and shading effectively demarcated Landolt-C clusters relative to a lack of demarcation in the unspaced strings, and that more clearly demarcated clusters (spaced followed by shaded) were initially fixated more centrally than non-demarcated clusters. These results suggest that the more easily a participant can identify the horizontal extent of an upcoming Landolt-C cluster, then the more centrally targeted the saccade will be to that cluster. Note that this holds even in a situation where the extent of all the clusters is constant. We will return to the question of why shading is a less effective demarcation cue than spacing in the *Discussion.*

Next, let us consider the landing position distributions for the target Landolt-C clusters (see Fig. 5). The most striking aspect of the data is that there are two quite distinct and differently shaped landing position distributions. For the spaced conditions, it is clearly the case that there are inverted-U shape distributions for both the high- and the low-frequency target clusters. In contrast, for the unspaced and shaded conditions, most fixations were made towards cluster beginning. Again, this pattern holds for high- and low-frequency clusters alike. Two points are obvious: First, saccadic targeting in Landolt-C cluster string scanning appears to be uninfluenced by the participant's familiarity with those clusters. Second, differential landing position distributions appear to be driven entirely by the presence or absence of spaces in Landolt-C strings.

Discussion

In the current Landolt-C learning and scanning paradigm, we manipulated exposure frequency of Landolt-C target clusters during learning, and cluster demarcation form during subsequent Landolt-C string scanning. Using this paradigm, we initially investigated how exposure frequency modulated the rate of learning abstract Landolt-C clusters and how this modulation effect changed over successive learning blocks. More importantly, we revisited whether cluster familiarity (frequency) affects eye-movement control in a visual search task using Landolt-C stimuli.

[5] To quantify the evidence in favour of the null effect of exposure frequency on the local measures, we undertook Bayesian LMM analyses (using *brms package,* version 2.15.0). We summarised the results of Bayesian LMMs by plotting the posterior distributions of the parameters of the model for each measure. The distributions overlaid with 95% credible intervals and posterior mean showed that plausible value 0 appeared within the 95% credible intervals for each measure we examined. These Bayesian LMM analyses favoured our conclusions of the null effect of exposure frequency that we drew from LMM analyses.

[6] We undertook an additional analysis by splitting the data into two sets based on whether participants made a 'hit' or a 'miss' decision with respect to a target. Almost all the results between the two groups were consistent with the results we report here (when the data were not split). One subtle difference occurred on first fixation duration within the 'miss' dataset. On these 'target undetected' trials, significantly shorter first fixation durations were observed on high-frequency clusters in spaced strings relative to shaded strings. However, no such spacing effect occurred on low-frequency clusters. Overall, these analyses indicate that regardless of whether we consider the behavioural responses in relation to accuracy, or in relation to hits and misses, we obtained very similar effects.

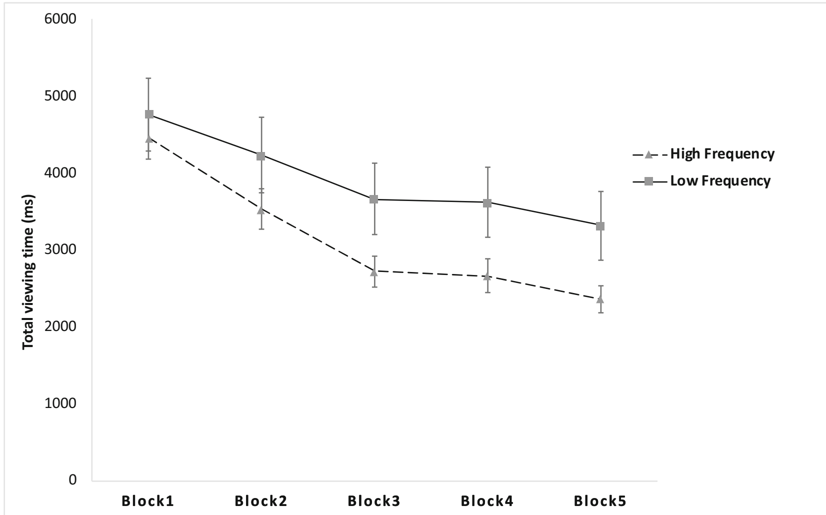

Fig. 3 Mean total viewing time during the learning of high-frequency and low-frequency target Landolt-C clusters across the five learning blocks. The vertical lines represent error bars

During the learning of target Landolt-C clusters, as we predicted, four exposures per learning block accelerated the rate of learning relative to just one exposure per learning block. Furthermore, the differential learning rate between high-frequency and low-frequency clusters increased over learning blocks. These results demonstrated that participants could learn nonsensical Landolt-C clusters; moreover, they responded less effectively (i.e., less accurate responses) to targets with fewer exposures than to targets with more exposures (cf., Vanyukov et al., 2012). The finding that participants can learn abstract stimuli is not novel; however, the finding that participants learnt stimuli with more exposures faster than those with fewer exposures is of significance. Vanyukov et al. (2012) reported similar differentially facilitative effects of 50 exposures over one exposure on processing time during target O search within linear Landolt-C strings. More recently, in relation to novel word learning, Hulme et al. (2019) reported that 38.5% of participants could correctly recall novel meanings of known words after just two exposures during story reading. Along with these studies, our data provide additional evidence for the claim that word frequency in reading accumulates via repeated exposures, with more exposures contributing to more consolidated representations in memory (Hulme et al., 2019; Inhoff & Rayner, 1986; Reichle & Perfetti, 2003; Vanyukov et al., 2012). The results also suggest that how immediately exposure frequency effects occur is likely a function of the depth to which they have been processed (Craik & Tulving, 1975). Admittedly, the three studies that we focus on here are quite different in a number of respects; however, it seems reasonable to suggest that the way exposure frequency affects processing in each of the different tasks is comparable at some level. Tentatively, we

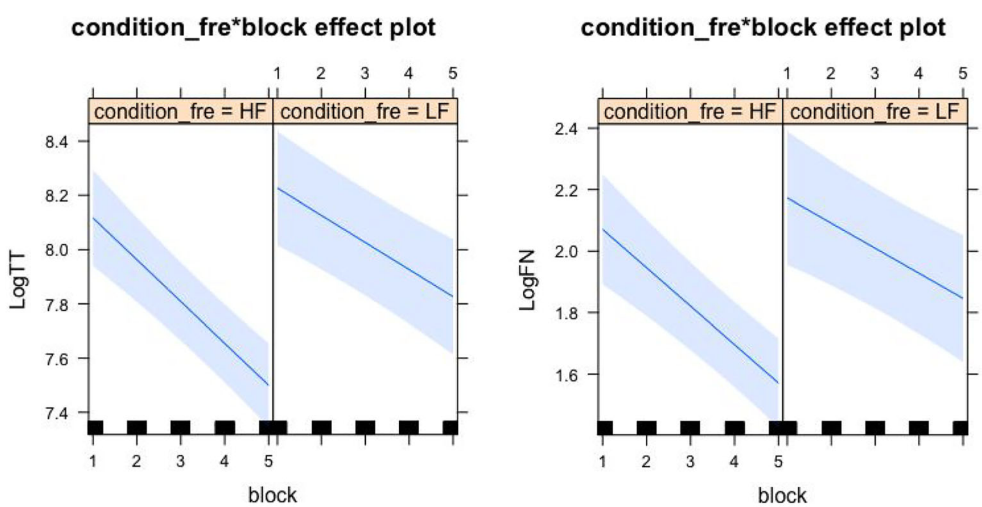

Fig. 4 The left panel plots the interactive effect between exposure frequency and learning block on log transformed total viewing time during target learning. The right panel plots the same effect observed on log transformed total fixation number. *HF* high frequency, *LF* low frequency

Table 3 Mean hit rate, means of RT, FFD, TT and fixation number in learning-assessment tasks

	High frequency			Low frequency		
	LAB 1 (4th)	LAB 2 (12th)	LAB 3 (20th)	LAB 1 (1st)	LAB 2 (3rd)	LAB 3 (5th)
Hit rate	0.60	0.73	0.75	0.46	0.53	0.60
	(0.04)	(0.04)	(0.03)	(0.04)	(0.03)	(0.04)
Reaction time	3914	3017	3070	4122	3540	3340
	(448)	(353)	(367)	(406)	(396)	(361)
First fixation duration	296	312	302	311	334	310
	(45)	(45)	(43)	(47)	(43)	(43)
Total viewing time	3568	2745	2804	3764	3242	2980
	(400)	(297)	(321)	(361)	(353)	(307)
Fixation number	9.3	6.9	7.2	9.8	8.3	7.8
	(1.2)	(0.8)	(0.9)	(1.0)	(1.0)	(0.9)

Note. LAB 1 refers to learning assessment block 1. LAB 2 refers to learning assessment block 2 and so forth

RT reaction time in making decisions, *FFD* first fixation duration, *TT* total viewing time

Fixation times are reported in milliseconds. Standard errors are given in parentheses

suggest that searching for a target O embedded in Landolt-C strings, (Vanyukov et al., 2012), might involve the shallowest form of cognitive processing, and consequently the emergence of exposure effects was quite delayed (i.e., significant

Table 4 Fixed effect estimates from generalised mixed-effect model (GLMM) on mean hit rate and linear mixed-effects models (LMMs) on reaction time in making decisions, first fixation duration, total viewing time and fixation number across targets in learning-assessment blocks

Dependent measure	*b*	*SE*	*t/z*
Hit rate			
Intercept	-0.15	0.18	-0.86
Frequency	-0.60	0.26	-2.26*
Block	0.33	0.06	5.53***
Frequency*Block	-0.10	0.12	-1.83
Reaction time			
Intercept	8.28	0.07	119.59***
Frequency	0.08	0.06	1.28
Block	-0.12	0.03	-4.56***
Frequency*Block	0.01	0.03	0.36
First fixation duration			
Intercept	5.47	0.07	74.95***
Frequency	0.11	0.09	1.19
Block	0.02	0.02	0.94
Frequency* Block	-0.02	0.04	-0.44
Total viewing time			
Intercept	8.19	0.07	124.36***
Frequency	0.09	0.06	1.56
Block	-0.12	0.02	-5.11***
Frequency*Block	0.00	0.03	0.07
Fixation number			
Intercept	2.19	0.10	22.18***
Frequency	0.10	0.06	1.61
Block	-0.12	0.03	-3.57**
Frequency*Block	0.00	0.03	0.03

Note. High frequency was the baseline for the analysis of frequency effects

*** p < .001, ** p < .01, *p < .05.

Table 5 Global measures from observations on all clusters and local measures from observations on target clusters during scanning.

Global measure				
		Unspaced	Shaded	Spaced
Mean fixation duration		358 (5)	342 (5)	327 (5)
Mean saccade amplitude		0.99 (0.03)	1.30 (0.05)	1.60 (0.05)
False alarm rate		0.38 (0.09)	0.39 (0.09)	0.40 (0.09)
Local measure				
		Unspaced	Shaded	Spaced
Hit rate	HF	0.50 (0.13)	0.44 (0.13)	0.47 (0.13)
	LF	0.41 (0.13)	0.42 (0.13)	0.44 (0.13)
First fixation duration	HF	371 (48)	348 (46)	319 (42)
	LF	359 (44)	334 (46)	333 (44)
Gaze duration	HF	1450 (290)	1022 (220)	1229 (245)
	LF	1390 (255)	1182 (265)	1233 (244)
Total viewing time	HF	2342 (346)	1745 (257)	2058 (310)
	LF	2311 (295)	1878 (298)	1946 (287)
Fixation number	HF	6.4 (1.0)	5.0 (0.8)	6.1 (0.9)
	LF	6.5 (0.9)	5.3 (0.8)	5.9 (0.9)
Incoming saccade length	HF	1.3 (0.1)	2.0 (0.2)	3.2 (0.2)
	LF	1.4 (0.2)	1.9 (0.2)	3.2 (0.2)
Outgoing saccade length	HF	1.5 (0.1)	2.2 (0.2)	3.1 (0.2)
	LF	1.5 (0.2)	2.0 (0.2)	3.2 (0.2)
Mean landing position	HF	0.7 (0.1)	0.9 (0.1)	1.8 (0.2)
	LF	0.6 (0.1)	0.8 (0.1)	1.6 (0.1)

Note. All the fixation times are reported in milliseconds. All the distances/amplitudes are measured in visual angle. The standard errors are given in parentheses

Table 6 Fixed-effect estimates from linear mixed-effect models (LMMs) on global measures and local measures

Global measure			
	b	*SE*	*t/z*
Mean fixation duration			
Intercept	5.82	0.03	210.17***
Shaded – Unspaced	-0.05	0.01	-3.85***
Spaced – Shaded	-0.04	0.01	-4.51***
Unspaced – Spaced	0.09	0.01	6.82***
Mean saccade amplitude			
Intercept	0.18	0.05	3.58***
Shaded – Unspaced	0.26	0.03	7.77***
Spaced – Shaded	0.20	0.02	9.97***
Unspaced – Spaced	-0.47	0.04	-12.22***
Local measure			
	b	*SE*	*t*
Hit rate			
Intercept	-0.25	0.18	-1.42
Frequency	-0.21	0.13	-1.69
Shaded – Unspaced	-0.11	0.15	-0.74
Spaced – Shaded	0.11	0.14	0.80
Unspaced – Spaced	-0.01	0.13	-0.04
Frequency* Shaded – Unspaced	0.32	0.25	1.31
Frequency* Spaced – Shaded	-0.03	0.24	-0.14
Frequency* Unspaced – Spaced	-0.29	0.24	-1.19
First fixation duration			
Intercept	5.71	0.03	194.43***
Frequency	-0.01	0.02	-0.13
Shaded – Unspaced	-0.09	0.03	-2.84**
Spaced – Shaded	-0.06	0.04	-1.60
Unspaced – Spaced	0.15	0.04	3.64***
Frequency*(Shaded – Unspaced)	-0.01	0.06	-0.02
Frequency*(Spaced – Shaded)	0.08	0.06	1.37
Frequency*(Unspaced – Spaced)	-0.08	0.06	-1.39
Gaze duration			
Intercept	6.70	0.09	78.21***
Frequency	0.04	0.04	1.03
Shaded – Unspaced	-0.35	0.05	-6.96***
Spaced – Shaded	0.11	0.05	2.21*
Unspaced – Spaced	0.24	0.05	-4.79***
Frequency*(Shaded – Unspaced)	0.11	0.10	1.07
Frequency*(Spaced – Shaded)	-0.04	0.10	-0.41
Frequency*Spacing 3	-0.07	0.10	-0.67
Total viewing time			
Intercept	7.31	0.11	66.01***
Frequency	0.02	0.03	0.53
Shaded – Unspaced	-0.36	0.06	-6.06***
Spaced – Shaded	0.13	0.06	1.99*
Unspaced – Spaced	0.24	0.06	-4.06***
Frequency*(Shaded – Unspaced)	0.03	0.07	0.48
Frequency*(Spaced – Shaded)	-0.09	0.07	-1.21
Frequency*(Unspaced – Spaced)	0.06	0.08	0.72
Fixation number			
Intercept	1.50	0.10	15.34***
Frequency	0.03	0.03	1.04
Shaded – Unspaced	-0.29	0.06	-5.27***
Spaced – Shaded	0.15	0.06	2.44*
Unspaced – Spaced	0.14	0.05	2.61**
Frequency*(Shaded – Unspaced)	0.07	0.07	0.98
Frequency*(Spaced – Shaded)	-0.11	0.07	-1.57
Frequency*(Unspaced – Spaced)	0.04	0.07	0.54
Incoming saccade length			
Intercept	3.97	0.05	87.77***
Frequency	0.02	0.03	0.72
Shaded – Unspaced	0.36	0.04	8.10***
Spaced – Shaded	0.54	0.06	8.55***
Unspaced – Spaced	-0.90	0.05	-16.74***
Frequency*(Shaded – Unspaced)	-0.09	0.07	-1.37
Frequency*(Spaced – Shaded)	0.04	0.07	0.88
Frequency*(Unspaced – Spaced)	0.04	0.07	0.55
Outgoing saccade length			
Intercept	4.01	0.05	84.22***
Frequency	-0.01	0.03	-0.55
Shaded – Unspaced	0.40	0.06	6.98***
Spaced – Shaded	0.44	0.07	6.73****
Unspaced – Spaced	-0.84	0.06	-13.78***
Frequency*(Shaded – Unspaced)	-0.04	0.06	-0.63
Frequency*(Spaced – Shaded)	0.07	0.06	1.17
Frequency*(Unspaced – Spaced)	-0.03	0.06	-0.51
Mean landing position			
Intercept	30.75	1.46	21.12***
Frequency	-0.49	0.84	-0.58
Shaded – Unspaced	7.09	1.31	5.40***
Spaced – Shaded	21.06	2.14	9.84***
Unspaced – Spaced	-28.15	2.33	-12.09***
Frequency*(Shaded – Unspaced)	-1.47	2.06	-0.71
Frequency*(Spaced – Shaded)	1.69	2.06	0.82
Frequency*(Unspaced – Spaced)	-0.22	2.07	-0.11

Note. High frequency was the baseline for the analysis of frequency effects

*** $p < .001$, ** $p < .01$, * $p < .05$

frequency effects emerged after 50 exposures). By contrast, learning novel meanings for known words almost certainly involves relatively deep linguistic processing, and presumably such processing contributed to more immediate exposure frequency effects (i.e., two exposures produced frequency effects). In the current study, we believe that the intentional learning of non-linguistic Landolt-C target clusters involved processing to a greater depth than simply searching for a target O, but shallower processing than learning novel meanings of known words during reading. Therefore, the influence of exposure on eye-movement control during the learning of Landolt-C clusters in the current study occurred earlier than the situation of searching for a target O, but less immediately than the situation of learning novel meanings of known words.

One thing that we can be certain about in the present study is that we effectively simulated exposure frequency effects through our exposure manipulation during the learning

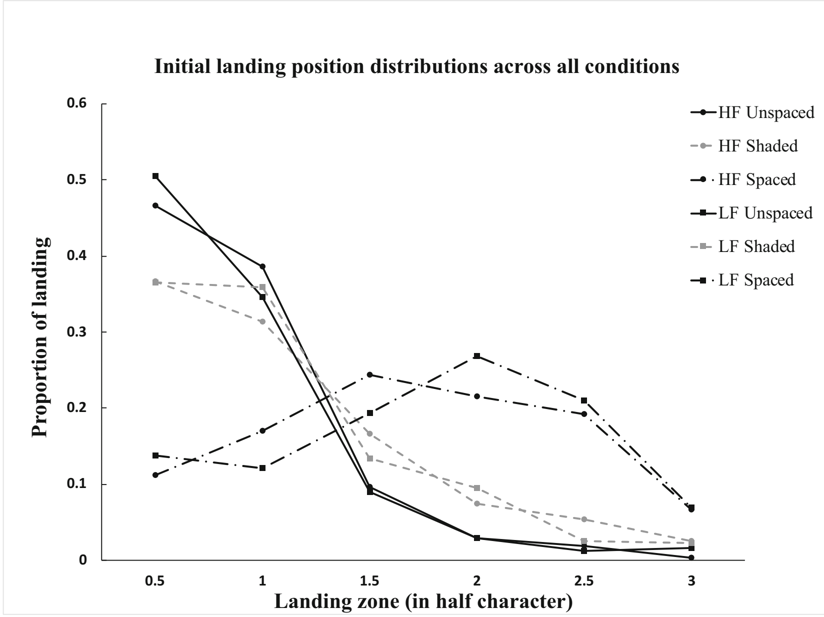

Fig. 5 The distribution of initial landing positions on target clusters across all the conditions in the scanning session. *HF* high frequency, *LF* low frequency

sessions. However, despite this, we failed to obtain robust frequency effects on eye-movement control when participants scanned Landolt-C strings in search for a target cluster. Recall that in the scanning scenario, participants were required to search for pre-learnt target clusters with greater, or lesser, levels of exposure in the learning session. Also, the Landolt-C strings were presented under different cluster demarcation conditions.

A 50% mean hit rate (and a 40% mean high false-alarm rate) in every condition indicated that our participants were unable to successfully perform the task. We consider that there are two major reasons why search performance was so poor during the scanning of Landolt-C strings. First, this is very likely because of the high visual similarity between distractor clusters and target clusters. Previous studies have demonstrated that search performance is substantially influenced by target-distractor similarity. Successful search is much more difficult when distractor stimuli are visually similar to the target relative to when they are dissimilar (Duncan & Humphreys, 1989; Neisser, 1963; Rayner & Fisher, 1987; Vanyukov et al., 2012; Williams & Pollatsek, 2007). In the present study, the visual distinctiveness of the current targets relative to distractors was entirely driven by unique combinations of gap orientations. Given the very high degree of similarity between targets and distractors, it is perhaps unsurprising search performance was poor in the scanning session, particularly given that target clusters were embedded within strings of eight other Landolt-C clusters.

The second reason why search performance was poor during Landolt-C strings scanning relative to learning was because there was change in the accuracy criterion across the two tasks. To be clear, in the learning session, participants were presented with a single Landolt-C cluster and they were required to decide as to whether they had already learnt the presented cluster. That is, for each cluster participants made a single decision. Furthermore, on 50% of trials a target was presented, and on 50% of trials a non-target was presented. To be explicit, the accuracy criterion was 50% (and we believe that under these circumstances the importance of accuracy in the task would be quite apparent to participants). In contrast, during scanning, participants were required to make up to nine decisions, one for each successive cluster, as to whether it was or was not a cluster that they had already learnt. Only one target cluster ever appeared in each string of nine clusters, and a target was embedded in a string on only 50% of scanning trials. Thus, participants were making a decision that a cluster was not a target on the vast majority of occasions that they considered a cluster, meaning that the accuracy criterion, at least at the level of decisions in relation to each individual cluster, in the search phase of the experiment was substantially reduced relative to that in the learning phase.

Next, let us consider why the exposure frequency of Landolt-C clusters did not affect eye-movement behaviour during target search. Recall that an important motivation of the current study was to investigate whether exposure frequency established during learning would be present in a sequential visual search task. There are several points to make here. As discussed earlier, for unspaced Landolt-C strings, participants had difficulty unambiguously identifying each particular set of three Landolt-Cs that formed a cluster. That is to say, as they scanned along the string, they may not have been certain where a potential target might have started and ended. Such ambiguity could have meant that identification of the target would have been very difficult and that frequency effects would have been diminished. However, the suggestion that failure to appropriately identify particular sets of three Landolt-Cs as potential target clusters could not have caused the null effects since target detection error rates were comparable across the unspaced, shaded and spaced conditions. Cluster demarcation provided by shading and spacing removed the ambiguity participants may have experienced under unspaced conditions. Thus, it seems unlikely cluster ambiguity contributed significantly to the lack of frequency effects.

To us, there appear to be three alternative, more compelling suggestions for why we did not obtain frequency effects during string scanning.[7] First, as mentioned earlier, our participants may have been unable to successfully identify arrays of clusters during scanning. On the assumption that cluster identification is a prerequisite for a frequency effect to occur, then a failure in cluster identification would mean that the opportunity for a frequency effect to occur never arose. An alternative possibility is that effects of frequency might have occurred, in which case, these would have reflected implicit effects, that is, an influence of frequency in the absence of any conscious awareness that a cluster was a target. However, given that such effects did not occur, our results offer no evidence to support the view that implicit processing of the target strings did occur. This leads us to an interesting point, namely, that establishing frequency effects for stimuli in search situations may depend on the extent to which the task requires an awareness of the identity of a target. For example, in the study by Vanyukov et al. (2012), where frequency effects did occur, participants were very aware of the identity of the target (an 'O' embedded in a Landolt-C cluster), as they were required to scrutinise each individual constituent element of a string. In contrast, in the present study, for which there was no evidence of frequency effects, the task required that Landolt-C strings be treated as multi-element clusters (rather like words), and not considered at the level of the individual elements comprising the string. It is in this way that it is possible that the nature of the task may be a determinant of the extent to which frequency effects occur.

A second suggestion is that our manipulation of exposure frequency during the learning blocks was not sufficiently effective to induce frequency effects for Landolt-C strings stored in memory. If this was the case, then we would not observe frequency effects for target strings regardless of the cluster demarcation forms under which they were presented. However, this explanation itself raises an interesting question, namely, why did we obtain frequency effects across blocks during learning, but not during string scanning? Presumably this would have to be because it is much more difficult to identify a target cluster embedded in a string of distractor clusters relative to making a recognition judgment in relation to a cluster presented in isolation. Consistent with the suggestion that target identification during scanning posed a significant challenge to our participants is the finding that fixation durations were much longer during the current Landolt-C target search relative to fixation duration data reported in other target search tasks (e.g., search through Z-strings and normal texts – Rayner & Raney, 1996; Rayner & Fischer, 1996; Vitu et al., 1995, and target O search in linear or circular Landolt-C arrays – Vanyukov et al., 2012; Williams et al., 2014; Williams & Pollatsek, 2007). The inflated fixation durations in current Landolt-C search indicated that to ascertain the presence of a target cluster amongst distractors was extremely difficult and required considerable processing beyond demands in previous studies.

A third possible explanation for the lack of frequency effects during string scanning may be that such effects simply do not occur when readers engage in scanning as opposed to reading behaviour. As mentioned earlier, several studies have failed to demonstrate frequency effects during scanning (Rayner & Fischer, 1996; Rayner & Raney, 1996; Wang et al., 2019). However, all these studies used linguistic stimuli (words) to assess frequency effects. To our knowledge, the only study other than the present that has investigated frequency effects using non-linguistic stimuli is that of Vanyukov et al. (2012), and counter to the more general pattern of effects, this study did show effects of frequency during scanning. Recall that in the Vanyukov et al. study participants searched for a target 'O' embedded in spaced Landolt-C quadruplets comprised of Cs with differing gap orientations and sizes manipulated across conditions. Here, quadruplet frequency exposure was manipulated via the frequency with which each quadruplet appeared as distractor in the strings to be scanned. To reiterate, under these conditions, frequency effects did materialise. Thus, perhaps for frequency effects to occur during non-linguistic string scanning, it must be manipulated via distractor rather than target clusters. Quite why this might be the case remains unclear. To summarise, our failure to obtain frequency effects in scanning in this experiment may have arisen due to the frequency exposure effect influencing individual cluster identity decisions, but not target discrimination decisions during scanning, or more simply because our task involved participants scanning a series of non-linguistic strings, or finally because we manipulated the frequency of target rather than distractor clusters.

Next let us consider our cluster demarcation results. The manipulation of cluster demarcation form produced very clear

[7] There was also a possibility that the lack of exposure frequency effects was due to memory interference, which would be far greater as trials accumulated with time. We therefore examined whether trial order would affect target detection performance in the scanning session. The results indicated that there was no significant difference on target detection performance between earlier trials and later trials. Thus, trial order did not affect target detection during scanning.

and robust effects on both fixation durations and fixation locations. The global analyses showed that scanning was most difficult in unspaced strings compared to spaced strings and shaded strings. More importantly, we also found a larger benefit for the spacing manipulation over the shading manipulation. That is to say, alternating shadings do facilitate scanning, but the degree of facilitation is reduced relative to that offered by the spacing manipulation. Interestingly, these data perfectly match the findings of spacing effects and shading effects on eye-movement control during reading in normally spaced languages. The removal of word spaces from languages that normally have them has been shown to produce substantial disruption to both word identification and saccadic targeting during reading. Furthermore, disruption associated with removing word spaces holds even when word boundaries are demarcated by alternating shading or colours (e.g., Drieghe et al., 2017; Perea et al., 2015; Perea & Acha, 2009; Rayner et al., 1998; Rayner & Pollatsek, 1996; Sheridan et al., 2016; Sheridan et al., 2013).

Demarcation cues such as spacing and shading may facilitate scanning for the following reasons: (1) they remove the need to perform Landolt-C cluster segmentation since cluster boundary cues are unambiguous and veridical; (2) knowing the beginning and end of a Landolt-C cluster ensures that the unit to be processed next is visually identifiable in the parafovea. This allows for optimised computation of oculomotor control metrics in relation to visual sampling. Saccade target selection is an aspect of oculomotor control that is critical for efficient scanning, and, thus, demarcation helps to reduce saccadic error; (3) explicit cluster demarcation reduces cross-cluster constituency ambiguity in Landolt-C cluster perception (i.e., which Cs belong with which cluster). Without cluster demarcation (either through shading or spacing), readers were uncertain as to whether adjacent Landolt-Cs formed strings that required evaluation against stored representations in memory for their possible identification.

Next, let us consider why alternating shadings were less effective in providing a cue to word boundaries relative to spaces between words. This is probably because processing a foveal cluster became more difficult when lateral masking and crowding occurred in the unspaced shaded conditions (see also Bricolo et al., 2015; Slattery & Rayner, 2013). Moreover, the lateral masking and crowding occurring in shaded conditions also impaired the visual salience of parafoveal clusters, consequently, reducing parafoveal visual processing of clusters. Therefore, a more cautious saccadic targeting strategy was more likely to be initiated during the scanning of shaded Landolt-C strings relative to spaced Landolt-C strings.

The current study is the first to demonstrate that saccadic targeting was mainly driven by spacing presentations in non-linguistic Landolt-C string scanning, and this is very comparable to what has been observed in a number of reading studies. In English reading, for spaced text readers ordinarily target saccades to the middle of a word – the so-called Preferred Viewing Location (PVL; Rayner, 1979), though when text is presented without spaces, readers target saccades towards word beginnings (e.g., Rayner et al., 1998). Furthermore, when readers make refixations on a word, the initial fixations are often made on word beginnings. This general pattern of findings is further qualified with respect to Chinese reading in that whether saccades are targeted to a word centre or to its beginning depends upon whether the reader makes a single fixation or a refixation on the word respectively, and this holds regardless of whether the same text is presented in a spaced or an unspaced format (see Zang et al., 2013). Perhaps the most striking aspect of the current findings in this context is that saccadic targeting patterns were very comparable to those observed for unspaced text even though cluster units were clearly demarcated in the parafovea using shading. Taken together, the present results alongside the existing studies lead us to conclude that spacing information plays a critical role in eye guidance during reading, and this influence generalises beyond reading to a non-linguistic visual search task.

Conclusion

In the present study, we effectively simulated an exposure frequency effect through training participants to learn abstract Landolt-C stimuli with different numbers of exposures over five learning blocks in a learning session.

During scanning of Landolt-C strings, somewhat unexpectedly, detection of pre-learnt target cluster within Landolt-C strings was quite poor across all conditions. This was very likely due to the high target-distractor similarity and an accuracy criterion shift between the two tasks. In line with existing studies showing failure to find frequency effects during target word search, the simulated exposure frequency did not affect eye-movement control in the current Landolt-C target search. During the scanning session, we did find very robust influences of the form of cluster demarcation both in relation to identification processes and saccadic targeting. Scanning was most difficult in the unspaced strings, less so for shaded strings and least for spaced strings. Distinctive landing position distribution patterns demonstrate that spacing is special in relation to saccadic targeting commitments during scanning, providing the most effective cue for saccadic guidance due to clear string boundary demarcation, reduced lateral masking and reduced crowding. Generally, our results indicate that eye-movement behaviour in the current Landolt-C search task is influenced by online cognitive processing difficulty (see also Vanyukov et al., 2012; William, & Pollatsek, 2007).

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