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The effect of letter string length and report condition on letter recognition accuracy

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Memory load

Abstract
Purpose: Letter sequence recognition accuracy has been postulated to be limited primarily by low-level visual factors. The influence of high level factors such as visual memory (load and decay) has been largely overlooked. This study provides insight into the role of these factors by investigating the interaction between letter sequence recognition accuracy, letter string length and report condition.
Methods: Letter sequence recognition accuracy for trigrams and pentagrams were measured in 10 adult subjects for two report conditions. In the complete report condition subjects reported all 3 or all 5 letters comprising trigrams and pentagrams, respectively. In the partial report condition, subjects reported only a single letter in the trigram or pentagram. Letters were presented for 100 ms and rendered in high contrast, using black lowercase Courier font that subtended 0.4° at the fixation distance of 0.57 m.
Results: Letter sequence recognition accuracy was consistently higher for trigrams compared to pentagrams especially for letter positions away from fixation. While partial report increased recognition accuracy in both string length conditions, the effect was larger for pentagrams, and most evident for the final letter positions within trigrams and pentagrams. The effect of partial report on recognition accuracy for the final letter positions increased as eccentricity increased away from fixation, and was independent of the inner/outer position of a letter.
Conclusions: Higher-level visual memory functions (memory load and decay) play a role in letter sequence recognition accuracy. There is also suggestion of additional delays imposed on memory encoding by crowded letter elements.

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PALABRAS CLAVE
Reconocimiento de la secuencia de letras;
Pentagramas;
Trigramas;
Crowding (amontonamiento);
Carga de la memoria

Efecto de la longitud de la cadena de letras y de la condición reportada sobre la precisión del reconocimiento de letras

Resumen
Objetivo: Se ha postulado que la precisión del reconocimiento de la secuencia de letras se ve limitada por los factores visuales de bajo nivel. La influencia de los factores de alto nivel, tales como la memoria visual (carga y deterioro) se ha ignorado en muchas ocasiones. Este estudio aporta mayor información sobre la función de dichos factores, al investigar la interacción entre la precisión del reconocimiento de la secuencia de letras, la longitud de la cadena de letras, y la condición reportada.
Métodos: Se midió la precisión del reconocimiento de la secuencia de letras para trigramas y pentagramas en 10 sujetos adultos, para dos condiciones de reporte. En la condición de reporte completa, los sujetos reportaron las 3 ó 5 letras incluidas en los trigramas y pentagramas, respectivamente. En la condición de reporte parcial, los sujetos reportaron únicamente una letra del trigrama o pentagrama. Las letras se presentaron durante 100 milisegundos en alto contraste, con fuente y letra minúscula Courier, subtendiendo 0,4 grados a una distancia de fijación de 0,57 m.
Resultados: La precisión del reconocimiento de la secuencia de letras fue consistentemente superior en los trigramas, en comparación a los pentagramas, y en especial para las posiciones de las letras alejadas de la fijación. A pesar de que el reporte parcial incrementó la precisión del reconocimiento en ambas situaciones de longitud de la cadena, el efecto fue superior en los pentagramas, y más evidente para las posiciones de la letra final de los trigramas y pentagramas. El efecto del reporte parcial en la precisión del reconocimiento para las posiciones de la letra final se incrementó a medida que se incrementó la excentricidad alejándose de la fijación, siendo independiente de la posición interna/externa de una letra.
Conclusiones: Las funciones de la memoria visual de mayor nivel (carga y deterioro de memoria) juegan una función en la precisión del reconocimiento de la secuencia de letras. Esto sugiere también unas demoras adicionales impuestas sobre la codificación de la memoria, por parte de los elementos del amontonamiento de letras.

Introduction

The process of visual based reading is a learned behavior which involves complex interactions between several processing systems which include (but is not limited to) letter processing, phonological processing, lexical processing, eye movements and contextual influences.[1]

Low level limitations imposed on reading processes by letter sequence recognition accuracy have been inferred from associations between the visual span and reading speed for both central and peripheral viewing.[2,3] The visual span is defined as the number of letters that can be correctly recognized at and on either side of fixation without the execution of an eye movement.[2–4] Essentially, the hypothesis posed by supporters of the theory assert that shrinkage in the size of the visual span is associated with proportional decreases in reading speed, possibly due to the need for more frequent fixations and saccadic eye movements,[2,3] specifically for paragraph reading. Indeed, both visual span and reading speed have shown similar dependency with retinal eccentricity, letter contrast, letter size, and interletter spacing.[2–5] Furthermore, developmental changes in the visual span also seemed to parallel developmental changes in reading speed.[6] Therefore, based upon these observations and others, it has been proposed that the visual span interacts as a causal factor by posing as a sensory bottleneck for visual information available to higher level processes.[2,3]

Typically, the sizes of visual spans in these studies have been computed from ''visual span profiles'' which plot letter recognition accuracy for letters presented at and on either side of fixation.[2,3] Furthermore, the visual spans in these studies have been confined to the use of trigrams which are random 3-letter strings. It is this observation that forms the basis of the current study. Letter recognition accuracy is known to decrease as string length is increased,[7] and reading rate of randomly presented words also decreases as word length increases for a given contrast.[4] Additionally, the average word length in English text is about 5.1 characters,[8] and the average word length of the 1000 most frequently used words in the Corpus of Contemporary American English is approximately 5.5. Furthermore, it is also known that memory load affects recall accuracy as a function of time following the presentation of the stimulus[9] and as a function of its serial position of presentation.[10,11] Additionally, depending on the cognitive task and the stimulus complexity, the human visual system exhibits a finite capacity to store short-term visual information, which in the case of letters

was also shown to be about 4–5 characters.[12,13] Hence, taken cumulatively, the above reports predict significant interactions between letter recognition accuracy and string length due to combined limitations imposed by both memory load (or capacity limitations) and memory decay. Furthermore, they also predict that report accuracy of letters comprising a string of characters should also show some dependence on the serial position of the letter within the string.

Therefore, the broad goal of this study was to investigate the role that memory (load and decay) will play in the report accuracy of two string length (trigrams and pentagrams) conditions. Manipulating the report condition enables an investigation of the effect of memory load on letter recognition accuracy. This study employed the partial and complete report methods.[14] With complete report all 3 or 5 characters were reported (in sequence) whereas in the partial report condition only a single pre-cued letter was reported. With partial report, the number of letters reported do not exceed current estimates of memory span, thereby equalizing (and minimizing) the memory load for both trigrams and pentagrams, while still preserving the contribution of other factors that have been identified previously as limitations of letter recognition accuracy.[3] Furthermore, the partial report procedure may also reduce the effects of memory decay as only a single character is reported.

Hence the specific aims of this study were:

(1) To quantify the effects of report condition on letter recognition accuracy for two string length conditions (random trigrams and pentagrams).
(2) To investigate the effect of report condition on letter recognition accuracy as a function of the serial position of a character within a trigram and pentagram.
(3) To investigate the effect of report condition on letter recognition accuracy as a function of the character's inner or outer position within a trigram and pentagram.

We hypothesized, if letter sequence recognition accuracy were determined solely by interactions of crowding, positional uncertainty and acuity limitations,[3] then report condition is expected to have very little to no effect on letter sequence recognition accuracy. In addition, we also hypothesized that if memory load (and decay) are factors that jointly influenced letter sequence recognition accuracy, then the effects of partial report will be larger with pentagrams vs. trigrams for comparable letter positions, and there should be an effect of report condition that varies with a character's serial position within a trigram or pentagram. Given that letter recognition accuracy also varies with its inner/outer position within a string[2,7,14]; therefore, we included the third aim to tease apart the effect of report condition on serial position from its effect on a character's inner/outer position.

Materials and methods

General methods

Letter recognition accuracy of 10 Optometry students were measured using random 3-letter trigrams and 5-letter pentagrams, using the method adopted by Legge et al.[2,3] All stimuli were presented on a 21 inch Dell Trinitron CRT monitor using a screen refresh rate of 120 Hz at a screen resolution of 1024×768. Each pixel subtended approximately 2 arc minutes at the fixation distance of 0.57 m. Letters were rendered in high contrast (0.84) black lowercase Courier font that subtended 0.4° (lowercase ''x''-height, ~12 pixels) at the fixation distance of 0.57 m. Courier font is a fixed width/monospaced font; as such inter-letter spacing is invariant with character type for a given font size. Furthermore, the choice of standard boldness Courier font represents an optimal stimulus characteristic for that font, with boldness significantly higher or lower than the standard boldness exhibiting adverse effects on reading speed.[15] The screen background was bright white (131 cd m^{-2}) for all viewing conditions. Inter-letter spacing was equivalent to standard spacing (~1.16X the width of a lowercase ''x'').[5] All letters were constructed using Matlab™, and presented using the psychophysics Toolbox option.[16,17] Stimulus duration was set to 100 ms for all conditions. The temporal presentation duration was calibrated with a photo-detector and an oscilloscope.

Subject selection

Subjects were graduate-level Optometry students between the ages of 23 and 28. The selection criteria included distance (4 m) and near (40 cm) VA's better than 20/25 OD, OS, OU, an absence of any heterotropia and a heterophoria between 2 prism diopters of esophoria and 8 prism diopters of exophoria as determined with alternating cover test at a distance of 50 cm. Subjects were required to have 40 arc seconds or lower of stereoacuity as measured using Wirt Rings along with at least 250'' random-dot stereoacuity measured using the Randot StereoTest™. Subjects were tested for overt reading abnormalities using sub-tests 1 through 5 of the Woodcock Johnson – WJ III Diagnostic Reading Battery™ test. Subjects were also asked about any past or existing reading, learning disorders, and/or developmental delays. Subjects had to perform above a 12 Grade Level Equivalent in the letter-word identification, word attack, reading vocabulary, passage comprehension, and reading fluency sub tests of the WJ III Diagnostic Reading Battery™ test, meet the visual acuity, binocular vision, and oculomotor criteria outlined above, and be free of known reading/learning disorders, to be eligible for participation in the study. All procedures were conducted with binocular viewing. Subjects provided written informed consent for voluntary participation in the study. The research was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki), and informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. Approval for the use of human subjects was granted by the Ferris State University institutional review board (IRB).

Measuring letter recognition accuracy with trigrams and pentagrams

Letter recognition accuracy in the present study was measured by adapting the ''trigram'' method proposed by Legge et al.,[2,3] Letter recognition accuracy was measured for

random 3-letter (trigrams) and 5-letter (pentagrams) strings presented on a computer screen at varying letter positions to the left and right of fixation (including fixation). All letters were randomly selected from a sample of all 26 letters comprising the English Alphabet for each letter comprising the trigram and pentagram. Repeated letters were allowed in trigrams and pentagrams, i.e. a trigram or pentagram sequence could include the same letter more than once.[a]

PROCEDURE: Prior to the presentation of each string sequence, subjects fixated between a pair of 6 arc minute fixation squares separated vertically by a space of 72 arc minute. In the case of the trigrams, the 3-letter string was randomly presented within 3 contiguous letter positions of 17 available positions tested. As an example, if the trigram ''tgu'' was centered at letter position 0 (Fig. 1A), then the center letter ''g'' of the trigram occupied the ''0'' position, the letter on the left (''t'') occupied letter position ''−1'' and the letter to the right (''u'') occupied letter position ''+1''. Each trigram was presented for 100 ms duration to prevent a saccadic movement to peripheral letter positions. Even though 17 letter positions were available (−8 to +8), only 13 letter positions (−6 through +6) were used in the analysis because it was only in these letter positions that the first, second and third letter of the trigram could be presented (furthermore, these letter positions were chosen to match those with pentagrams). Therefore each trigram was presented with either its first, second or third letter occupying each of 13 letter positions. Subjects entered their perceived sequence of letters using the keyboard, which then allotted a score of ''1'' for each letter entered correctly in its correct sequence and a score of ''0'' for every incorrect letter. The proportion of correct responses was tallied for each serial position within the trigram and for each letter position relative to fixation. For any given letter position relative to central fixation, a single block of trials comprised 15 repetitions when that letter position was occupied by the first through third letter of the trigram sequence.

In the case of the pentagrams, each string comprised random 5-letter sequences. The pentagram strings were presented at the same letter positions relative to fixation

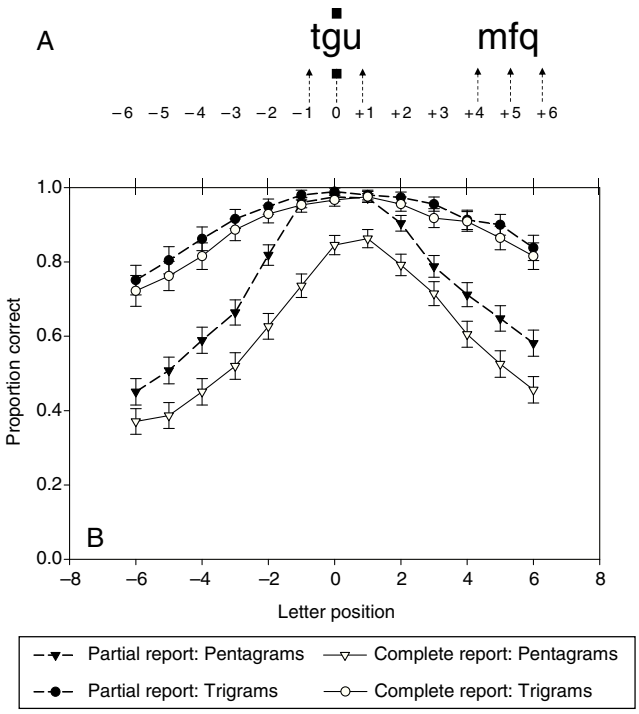

Figure 1 (A) An illustration depicting the stimulus setup for the trigrams. As an example trigram ''tgu'' is presented at letter positions −1, 0, and +1 relative to fixation. An additional example is also provided of trigram ''mfq'' presented at letter positions +4, +5, and +6. In this case, the letter ''m'' is the inner letter while the letter ''q'' is the outer letter. Letter positions to the left of fixation are denoted by negative values, and those presented to the right of fixation by positive values. The 1st serial position always refer to the leftmost letter within a trigram or pentagram, and increases progressively, in sequence to the rightmost letter. (B) Proportion correct (±95% CI) letter sequence recognition for trigrams (circles) and pentagrams (triangles) are plotted as a function of letter position relative to fixation, and separated according to report condition (Complete report: unfilled symbols with solid lines, Partial report: Filled symbols with dashed lines). Data are pooled across 10 subjects.

as outlined for the trigrams. Stimulus duration was 100 ms. Even though 21 letter positions were available (−10 to +10), only 13 letter positions (−6 through +6) were used in the analysis because it was only in these letter positions that the first, second, third, fourth, and fifth letter of the pentagram could be presented. For any given letter position, a single block of trials comprised 15 repetitions when that letter position was occupied by the first through fifth letter of the pentagram sequence.

Two report conditions were conducted for both trigrams and pentagrams. During the ''*complete report*'' condition, subjects were required to record all three or all 5 letters comprising the trigram or pentagram in their correct sequence, respectively. During the ''*partial report*'' condition, subjects were required to record only one letter of the trigram or pentagram within a given block of trials i.e. within a given block of trials subjects had to report either the 1st, 2nd or 3rd letter of the trigram sequence, or only the 1st, 2nd, 3rd, 4th, or 5th letter of the pentagram sequence.

[a] Response errors could be introduced in the partial report condition if, for example, subjects reported the 3rd serial position instead of reporting the letter at the pre-cued 1st serial position. In this case, if the same letter were presented at the 1st and 3rd serial position within a trigram, then a subject's response would be scored as correct if he/she reported the 3rd serial position instead of the 1st serial position. A Matlab simulation was conducted, using the same randomization protocol that generated trigrams and pentagrams in the study, to quantify the percentage of times the same letter appeared twice or three times within a given trigram for 6000 randomly generated sequences. The simulation suggested that <4% of the sequences contained the same letter twice, and 0.13% of the sequences contained the same letter in all 3 serial positions of trigrams. The same simulation was also conducted for 6000 randomly generated pentagrams, and <3.5% of the sequences contained the same letter twice, 1.13% contained 3 repeated letters, and less than 0.04% contained 4 or 5 repeated letters. As such, errors associated with repeated letters are small. These errors are distributed across the 3 or 5 serial position combinations in trigrams or pentagrams, respectively, and across 13 letter positions relative to fixation.

Subjects were informed which serial letter position was to be reported prior to the start of each ''*partial report*'' procedure. A separate block of trials was completed for each serial letter position comprising the trigram and pentagram sequence. A single block comprised 15 repetitions for each serial letter position (relative to its position within a trigram or pentagram) presented at each of 13 letter positions relative to central fixation (−6 to +6). Correct letter recognition data for each serial letter position within a trigram or pentagram was then collated for each letter position (−6 to +6) relative to central fixation. All stimulus parameters for the ''*partial report*'' condition were identical to the ''*complete report*'' condition.

All subjects were trained with all experimental conditions prior to data collection. Subjects were instructed prior to each data collection session to maintain steady fixation between the fixation squares, however, small in accuracies in fixation cannot be ruled out given that eye tracking was not used to monitor fixation. Additionally, a pilot study ($n = 5$) found no statistically significant differences between letter recognition accuracy of trigrams and pentagrams when subjects entered their responses using the keyboard vs. verbal reports by subjects (in this case entries were made by the experimenter). In the case of trigrams, a two way repeated measures ANOVA (Response method (Keyboard vs. Verbal) X letter position) showed no significant main effect of Response method ($F(1,129) = 5.167$, $p = 0.085$), a significant effect of letter position ($F(12,129) = 12.487$, $p < 0.001$), and no interaction effect between Response method and letter position ($F(12,129) = 0.639$, $p = 0.798$). Similarly, in the case of pentagrams, there was no significant main effect of Response method ($F(1,129) = 7.433$, $p = 0.053$), a significant effect of letter position ($F(12,129) = 47.784$, $p < 0.001$), and no interaction effect between Response method and letter position ($F(12,129) = 1.142$, $p = 0.351$).

Results

Letter recognition accuracy for trigrams and pentagrams

Proportion of correct letter recognition was taken as a measure of letter recognition accuracy. As illustrated in Fig. 1A, letter position relative to fixation refers to the position occupied by a letter in the visual field expressed in units of letter positions relative to the point of fixation (i.e. letter position '0'). Letter recognition accuracy (±95% CI) for both trigrams and pentagrams for each report condition are plotted in Fig. 1B for 13 letter positions relative to fixation (−6 to +6) pooled across 10 subjects. Each datum in Fig. 1B represents the cumulative proportion (±95% CI) for all 3 letters of a trigram and all 5 letters of a pentagram presented at each letter position relative to fixation. Therefore, the proportion of correct responses was derived from a total of 45 (15×3) presentations for trigrams and 75 (15×5) presentations for pentagrams for each subject.

A Mann Whitney Rank sum test on the raw scores of 10 subjects across 13 letter positions indicated a significant effect of report condition (Median Partial Report = 42, Median Complete Report = 41, $U = 7084.5$, $p = 0.024$). Similarly, there was a significant effect of report condition for pentagrams (Median Partial Report = 54, Median Complete Report = 43.5, $U = 5236.5$, $p < 0.001$). A Kruskal–Wallis One Way ANOVA on the raw scores of 10 subjects also showed a significant effect of letter position in trigrams (Partial Report: $H = 97.625$, $df = 12$, $p < 0.001$; Complete Report: $H = 80.068$, $df = 12$, $p < 0.001$) and pentagrams (Partial Report: $H = 117.215$, $df = 12$, $p < 0.001$; Complete Report: $H = 112.864$, $df = 12$, $p < 0.001$).

To assess the effect of report condition on the overall area of the letter recognition profiles depicted in Fig. 1B, the proportion correct for the left letter positions (−6 to 0) and right letter positions (0 to +6) for each subject's data were fit separately with a best-fit Gaussian function by minimizing the sum of the squared errors. The total area (A_T) under each fitted function was then computed as follows:

$$A_T(x) = \left[\int_{-6}^{0} P_{\max\ left} * \exp\left(\frac{(-x_L)^2}{2 * \sigma_L^2}\right)\right] + \left[\int_{0}^{6} P_{\max\ right} * \exp\left(\frac{(-x_R)^2}{2 * \sigma_R^2}\right)\right]$$

$P_{\max\ left}$, peak amplitude for left fit; $P_{\max\ right}$, peak amplitude for right fit; σ_L, standard deviation for left fit; σ_R, standard deviation for right fit; x_L, left letter positions (−6 to 0); x_R, right letter positions (0 to +6).

Table 1 tabulates the mean left, right and total areas (±95% CI) for each report condition in trigrams and pentagrams. A one-way repeated measures ANOVA was conducted on the total area for each trigram report condition. There was a significant effect of report condition on the area of the trigram letter recognition profiles ($F(1,19) = 8.899$, $p = 0.015$), with partial report increasing the mean area of letter recognition profiles by about 3%. Similarly, a one-way repeated measures ANOVA conducted on the total area for each pentagram report condition showed a significant effect of report condition on the area of the pentagram letter recognition profiles ($F(1,19) = 128.382$, $p < 0.001$), with partial report increasing the mean area of letter recognition profiles by about 21%.

Hence, letter recognition accuracy decreased with increasing eccentricity away from fixation regardless of report condition for both string lengths. Partial report increased letter recognition accuracy for both trigrams and pentagrams, but to a greater extent with pentagrams. The magnitude of improvement in letter recognition accuracy with partial report displayed left/right asymmetry and will be commented on in the following section. As a side note, a pilot study was conducted using isolated letters presented at each letter position relative to fixation. Letter recognition accuracy showed almost perfect performance across all 13 letter positions, hence acuity was not a limiting factor in this study.

Laterality asymmetry and the effect of report condition

Laterality refers to the hemi-field in which a letter was presented. All letter positions to the left of the zero

Table 1 Mean left, right and total areas (±95% CI) for trigrams and pentagrams calculated for the complete and partial report conditions. Data are pooled across 10 subjects.

	Trigrams		Pentagrams	
	Partial report	Complete report	Partial report	Complete report
Left area	5.3814 (±0.122)	5.1993 (±0.178)	4.3015 (±0.135)	3.405 (±0.204)
Right area	5.6306 (±0.065)	5.509 (±0.120)	4.8298 (±0.134)	4.1637 (±0.253)
Total area	11.012 (±0.170)	10.7083 (±0.282)	9.1314 (±0.170)	7.5687 (±0.282)

position (−6 to −1 in Fig. 1A and B) fall in the left hemi-field, while all letters presented to the right of the zero position (1–6 in Fig. 1A and B), fall in the right hemi-field. It is evident from Fig. 1B that letter recognition accuracy for the complete report condition is higher on the right of fixation compared to the left of fixation, an observation that is consistent with previous report.[2,5] In an attempt to investigate if report condition exerted different effects on letter recognition accuracy in the L and R hemi-fields, a two-way repeated measures ANOVA (Report condition × Laterality) was conducted separately for trigrams and pentagrams on the area as a function of laterality and report conditions (Table 1).

In the case of trigrams, there was a significant increase in area with partial report ($F(1,39) = 8.89$, $p = 0.015$). There was also a significant effect of laterality ($F(1,39) = 33.96$, $p < 0.001$), with the right field displaying a larger area than the left field. The interaction effect between report condition and laterality was not significant ($F(1,39) = 1.398$, $p = 0.267$). However, using the Holm–Sidak Pairwise Multiple Comparison method, the effect of partial report seemed to be confined to the left hemi-field ($t = 3.197$, $p = 0.007$) but not the right hemi-field ($t = 2.135$, $p = 0.052$). In the case of pentagrams, a similar analysis revealed a significant increase in area with partial report ($F(1,39) = 128.38$, $p < 0.001$), which was significant in both left ($t = 11.034$, $p < 0.001$) and right hemi-fields ($t = 8.198$, $p < 0.001$) (Holm–Sidak Pairwise Multiple Comparison method). Furthermore, similar to trigrams, the right field displayed a larger area compared to the left field ($F(1,39) = 53.94$, $p < 0.001$) regardless of report condition. The interaction effect between report condition and laterality was also significant ($F(1,39) = 7.186$, $p = 0.025$). In summary, both trigrams and pentagrams displayed a right field advantage, and while partial report improved letter recognition accuracy in both hemi-fields for pentagrams, the improvement appears to be more evident in the left field in trigrams.

Serial position and the effect of report condition

Serial position refers to the position occupied by a letter within a trigram or pentagram. The left-most letter in a trigram and pentagram is always serial position 1, and the serial position of subsequent letters increase sequentially to the right. This concept is illustrated in Fig. 1A, which uses the example of trigram 'tgu' presented at letter positions −1, 0 and +1 relative to fixation. In this case, the letter 't' is serial position 1, the letter 'g' is serial position 2, and the letter 'u' is serial position 3. The same nomenclature applies to pentagrams; however, serial positions will increase sequentially from left to right up to 5.

In an attempt to analyze the effect of report condition on letter recognition accuracy for each serial position of the trigram and pentagram, letter recognition profiles (similar to Fig. 1B) were constructed separately for each serial position of the trigram (Fig. 2A–C) and pentagram (Fig. 3A–E). Gaussian functions were fit to the letter recognition profiles for each serial position and report condition to calculate the area under the best fit function using the method described earlier. Figs. 2D and 3F plots the mean total area (±95% CI) for each serial position of a letter within the trigram and pentagram separated according to report condition, respectively.

Consistent with previous report,[7] letter recognition accuracy was lower for the middle serial positions regardless of string length and report condition compared to the initial and final letter positions within each string length condition, i.e. serial position 2 for trigrams (Fig. 2D) and serial positions 2, 3, and 4 for pentagrams (Fig. 3F) (Two Factor repeated measures ANOVA (Serial position × Report condition) using the Holm–Sidak Multiple comparison method: Trigrams: 1st letter vs. 2nd letter ($t = 8.9$, $p < 0.001$), 3rd letter vs. 2nd letter ($t = 5.158$, $p < 0.001$)), Pentagrams: 1st letter vs. 2nd letter ($t = 16.717$, $p < 0.001$), 3rd letter ($t = 26.578$, $p < 0.001$) and 4th letter ($t = 24.085$, $p < 0.001$), and the 5th letter vs. 2nd letter ($t = 4.592$, $p < 0.001$), 3rd letter ($t = 14.453$, $p < 0.001$) and 4th letter ($t = 11.960$, $p < 0.001$). Furthermore, recognition accuracy of the 1st and 2nd letters in trigrams (Fig. 2A, B and D) and pentagrams (Fig. 3A, B and E) was unaffected by report condition regardless of the hemi-field in which they were presented Two Factor repeated measures ANOVA (Serial position × Report condition) using the Holm–Sidak Multiple comparison method (Complete vs. Partial Report): Trigram: 1st letter ($t = 0.153$, $p = 0.879$), 2nd letter ($t = 1.306$, $p = 0.203$); Pentagram: 1st letter ($t = 0.300$, $p = 0.765$), 2nd letter ($t = 0.519$, $p = 0.606$). Partial report had the most consistent effect on the 3rd letter position in trigrams ($t = 4.488$, $p < 0.001$) and the 3rd ($t = 2.614$, $p = 0.012$), 4th ($t = 10.692$, $p < 0.001$) and 5th ($t = 14.770$, $p < 0.001$) letter in pentagrams. The 3rd serial position in trigrams contributed to about 77% of the increase in total area with partial report, whereas the 4th and 5th letters within pentagrams cumulatively accounted for approximately 88% of the increase in total area with partial report. An additional observation that can be gleaned from inspection of Figs. 2(A–C) and 3(A–E) is that for the ''0'' abscissa value (central fixation), letter recognition accuracy for all 3 serial positions in trigrams is close to perfect performance for the complete report procedure, however, in the case of

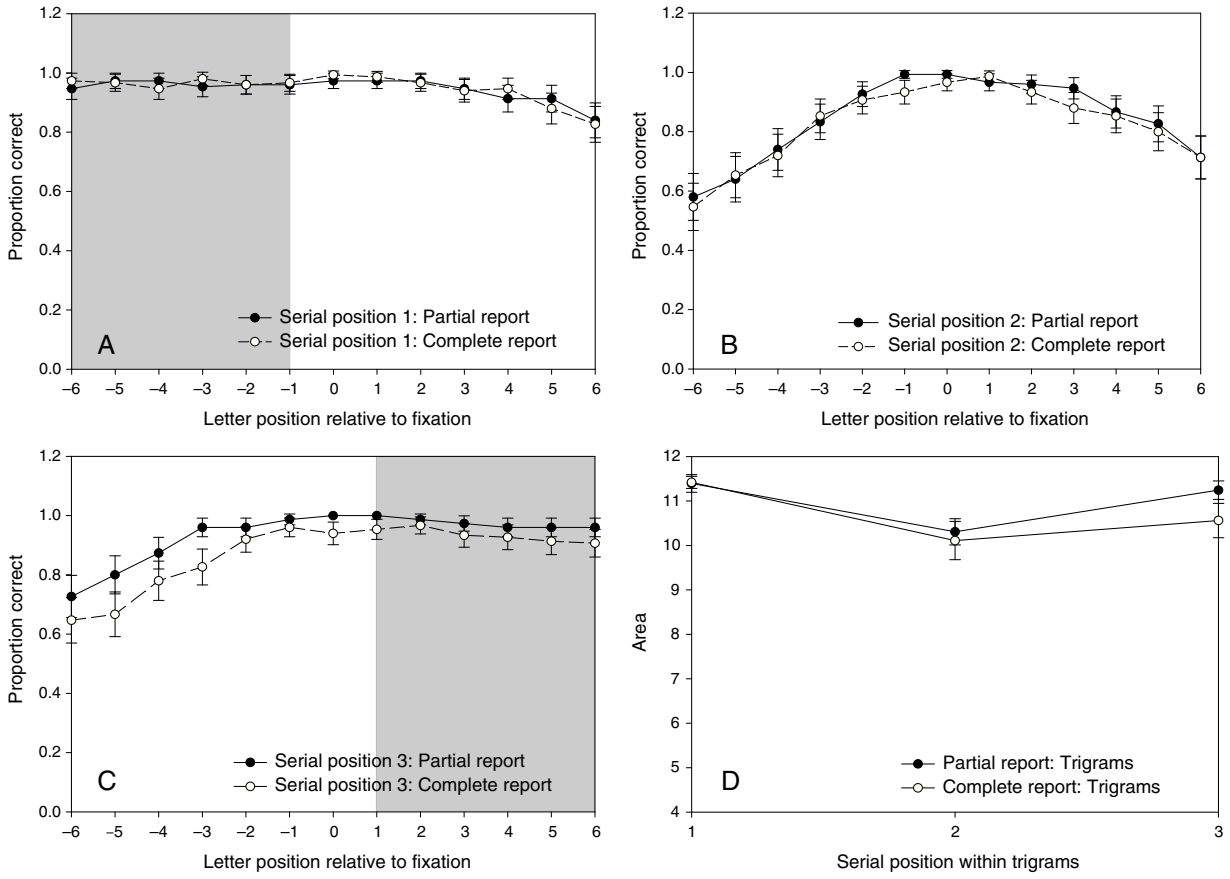

Figure 2 (A–C) Proportion correct (±95% CI) letter recognition for the two report conditions (Complete: unfilled symbols, Partial: filled symbols) is plotted as a function of letter position relative to fixation for each serial position in trigrams (A–C). D plots the mean total area (±95% CI) calculated for each serial position of the trigram. Data are pooled across 10 subjects.

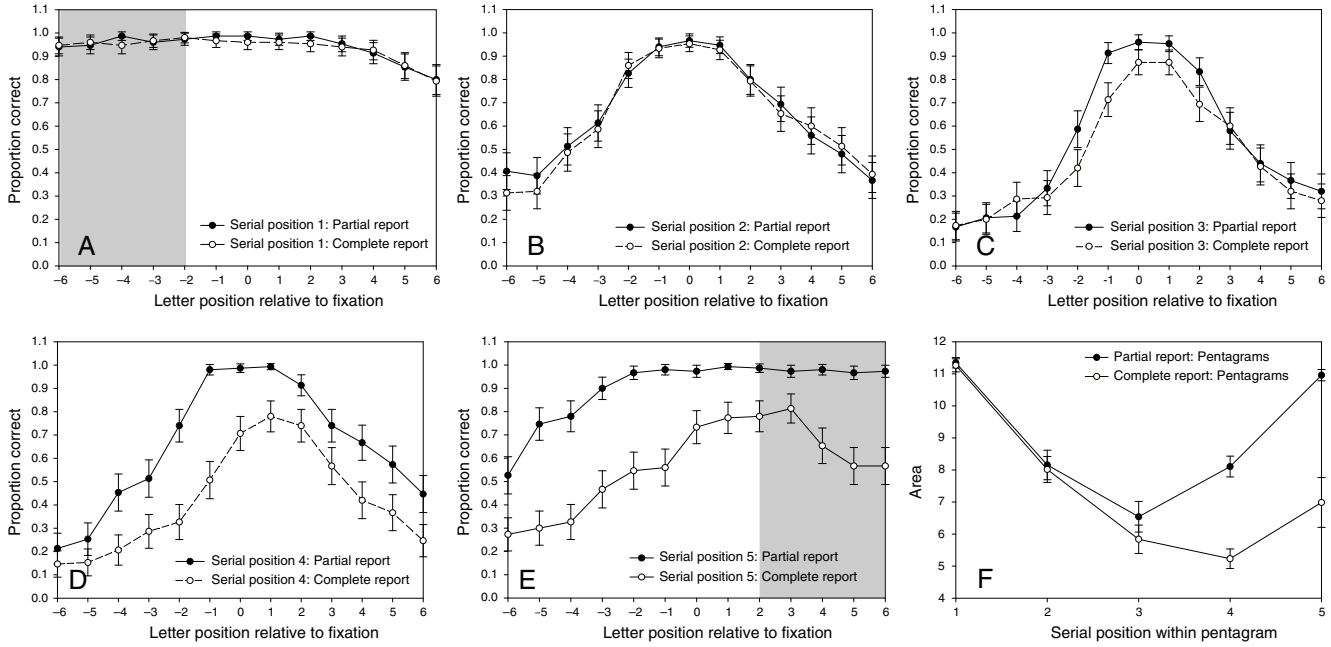

Figure 3 (A–E) Proportion correct (±95% CI) letter recognition for the two report conditions (Complete: unfilled symbols, Partial: filled symbols) is plotted as a function of letter position relative to fixation for each serial position in pentagrams (A–E). F plots the mean total area (±95% CI) calculated for each serial position of the pentagram. Data are pooled across 10 subjects.

pentagrams, there was a systematic decrease in letter recognition accuracy from serial positions 1–5 (specifically for serial positions 3–5). The limitations imposed by acuity and positional uncertainty are deemed negligible at foveal fixation (abscissa value of 0 in Figs. 2(A–C) and 3(A–E)) and are therefore unlikely contributors to any observed decreases in letter recognition accuracy at fixation. Furthermore, it is also arguable that foveal crowding/masking at fixation is also of small magnitude in this case given the almost perfect performance with trigram letters presented at fixation, and the perfect performance of pentagram letters presented at fixation observed with the partial report condition. Therefore, the authors propose that the result observed with pentagrams is a manifestation of the combined limitations imposed by memory load and decay which are significant for centrally presented pentagrams, but negligible for centrally presented trigrams. Furthermore, it also appears that memory (load and decay) seem to exert an increasingly adverse effect on letter recognition with increasing eccentricity relative to fixation. This observation also seems true for trigrams, specifically in the left hemifield.

The accuracy of letter recognition within a string of characters also depends on the distance of its initial and final letters from the fovea (or fixation).[2,7] inner letters are typically associated with lower letter recognition accuracy compared to outer letters. A letter within a trigram or pentagram is termed an inner letter if its position is closer to the fovea or fixation point than any other letter within the same trigram or pentagram. Similarly, a letter within a trigram or pentagram is termed an outer letter if its position is furthest from the fovea or fixation point compared to any other letter within the same trigram or pentagram. As an example consider trigram ''mfq'' (Fig. 1A), the 1st letter ''m'' of the trigram is closest to fixation (letter position 0) and the 3rd letter ''q'' is furthest from fixation. Therefore in this case, the first letter ''m'' is the inner letter and the 3rd letter ''q'' is the outer letter. Similarly, this classification scheme can also be extended to pentagrams. In conditions where a trigram occupied letter positions −1, 0 and +1, and a pentagram occupied letter positions −2, −1, 0, +1 and +2, the first and last letters within each string length will be equidistant from fixation. In these cases, both the first and final letters were classified as inner and outer letters for the purposes of this report. given that inner and outer letters co-vary with the serial position of letter and its letter position relative to fixation, therefore it is instructive to separate the effects of these 3 variables on letter recognition accuracy.

Interaction between letter position relative to fixation, serial letter position and its inner/outer position

The shaded regions in Figs. 2(A and C) and 3(A and E) represents outer letters when occupied by the 1st (Figs. 2A and 3A) and last letter (Figs. 2C and 3E) within a trigram or pentagram, respectively. It follows that the unshaded regions represent the inner letters. Two observations are fairly evident from Figs. 2(A and C) and 3(A and E). The first observation is consistent with previous report in that letter recognition accuracy was generally higher when the letter was an outer letter compared to the condition where the letter was an inner letter, for both trigrams and pentagrams.[2,7] A Two-way Repeated Measures ANOVA (inner/outer Position × Letter Position) was conducted on the raw scores for the complete report condition with trigrams and pentagrams. There was a significant main effect of the inner/outer position of a letter (Trigram: $F(1,239) = 41.692$, $p < 0.001$; Pentagram: $F(1,199) = 76.001$, $p < 0.001$), a significant main effect of letter position relative to fixation (Trigram: $F(11,239) = 12.850$, $p < 0.001$; Pentagram: $F(9,199) = 16.226$, $p < 0.001$), and a significant interaction effect between letter position relative to fixation and the inner/outer position of a letter (Trigram: $F(11,239) = 10.987$, $p < 0.001$; Pentagram: $F(9,199) = 53.974$, $p < 0.001$). Using the Holm–Sidak pairwise multiple comparison method, significant differences ($p < 0.05$) in recognition accuracy were found between inner and outer letters when they occupied letter positions −6 to −3, and +6 for trigrams, and letter positions +2 to +6 and −2 to −6 for pentagrams for the complete report condition. The main effects of inner/outer position and letter position relative to fixation, including their interaction effects were also significant ($p < 0.001$) for the partial report condition in both trigrams and pentagrams. Using the Holm–Sidak pairwise multiple comparison method, significant differences ($p < 0.05$) in recognition accuracy were found between inner and outer letters when they occupied letter positions −6 to −4, and +6 for trigrams, and letter positions +5 to +6 and −4 to −6 for pentagrams.

Secondly, the increase in letter recognition accuracy with the partial report condition depended on the serial position of the letter within the trigram or pentagram, and not whether the letter occupied the inner or outer position within the trigram or pentagram, i.e. recognition accuracy was higher for the final letter positions with partial report regardless of its inner/outer position. A Two-way Repeated Measures ANOVA (Report condition × Letter Position) was conducted separately on the raw scores for the 1st and 3rd serial positions in Trigrams and the 1st and 5th serial position in pentagrams. The analyses were also separated according to the inner and outer positions of these serial positions. When the letter occupied an inner position there was no effect of report condition for the 1st serial position in trigrams ($F(1,159) = 0.0347$, $p = 0.856$) and pentagrams ($F(1,179) = 0.628$, $p = 0.448$). However, there was a significant effect of report condition for the 3rd serial position in trigrams ($F(1,159) = 13.613$, $p = 0.005$) and the 5th in pentagrams ($F(1,179) = 73.053$, $p < 0.001$). Similarly, when the letter occupied an outer position, there was no effect of report condition for the 1st serial position in trigrams ($F(1,119) = 0.171$, $p = 0.689$) and pentagrams ($F(1,99) = 0.009$, $p = 0.923$), but a significant effect of report condition for the 3rd serial position in trigrams ($F(1,119) = 10.962$, $p = 0.009$), and the 5th in pentagrams ($F(1,99) = 119.11$, $p < 0.001$). This result is demonstrated more clearly in Fig. 4A–D which plots the proportion correct (±95% CI) for the complete report condition against the respective partial report condition for inner letters (4A and C) and outer letters (4B and D). Data points falling on the straight line represent no change in letter recognition accuracy with partial report, whereas data points above the straight line represent higher letter recognition accuracy

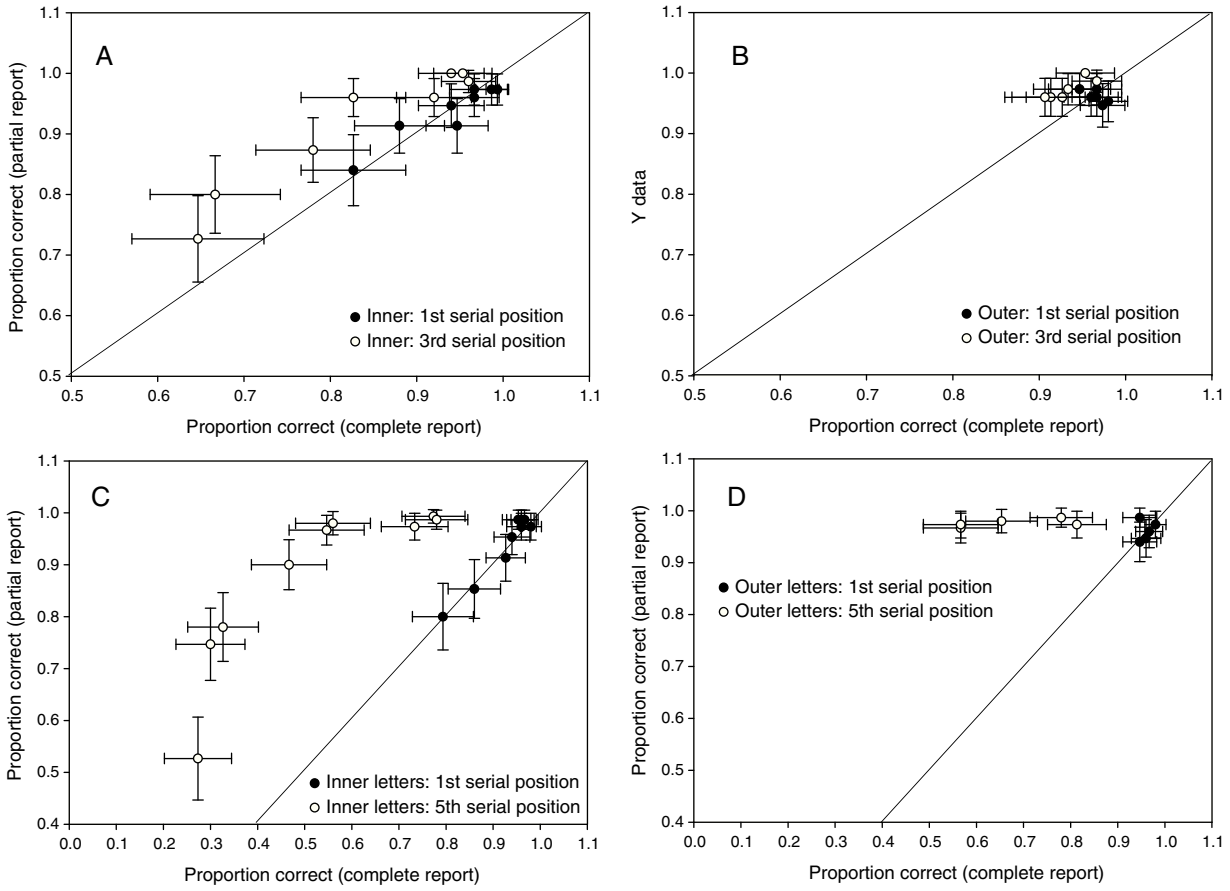

Figure 4 (A–D) Proportion correct (±95% CI) for the complete report condition is plotted against the proportion correct (±95% CI) for its respective partial report condition. The 1st serial position (filled symbols) and the last (3rd or 5th) serial position (unfilled symbols) within trigrams (A and B) and pentagrams (C and D) are separated according to whether it was an inner (A and C) or an outer letter (B and D). Data points falling on the straight line represent no change in letter recognition accuracy with partial report, whereas data points above the straight line represent higher letter recognition accuracy with partial report compared to complete report. Data are pooled across 10 subjects.

with partial report compared to complete report. It is evident that the influence of partial report is confined to the last serial position (3rd in a trigram and 5th in a pentagram) regardless of whether it was an inner or outer letter.

Hence, the effect of report condition primarily affects report accuracy for the final letter position in both trigrams and pentagrams. Furthermore, the increase in report accuracy observed with partial report does not depend on whether a letter occupied an inner or outer position within its string.

Discussion

This study had 3 specific aims: To quantify the effects of report condition on letter recognition accuracy for two string length conditions, to investigate the effect of report condition on letter recognition accuracy as a function of the serial position of a character within trigrams and pentagrams, and to investigate the effect of report condition on letter sequence recognition accuracy as a function of a character's inner or outer position within a trigram and pentagram. The results show clearly that letter recognition accuracy declines significantly with an increase in string length from 3 to 5 characters, being most evident for comparable letter positions at increasing viewing eccentricity. Furthermore, the improvement in letter recognition accuracy was confined to the latter serial positions in both trigrams and pentagrams, with arguably no effect on the first 2 letter positions. The effect of report accuracy did not depend on whether a letter was an inner or outer letter.

A previous report has suggested that letter recognition accuracy is limited primarily by low-level visual factors, namely, acuity limitations, positional uncertainty and crowding, especially with increasing viewing eccentricity.[3] While the current study did not specifically investigate each of these factors, there are several observations in the present results that appear consistent with these postulated limitations, especially that of crowding. Recognition accuracy of the middle serial positions (2 in trigrams, and 2, 3, and 4 in pentagrams) is consistently reduced with respect to the 1st and last serial positions, as evidenced by the ''U-shaped'' functions derived for both the complete and partial report data (Figs. 2D and 3F). This effect was larger as viewing eccentricity increased (inferred from Figs. 2A–C and 3A–E) relative to the fixation point. These

results are consistent with reports implicating the role of crowding as a significant factor for these serial positions of a letter within a string[14,18]; and with reports showing that both the magnitude of crowding and size of the crowding zones increasing with viewing eccentricity.[19]

Notwithstanding the above, there are two observations in the present study that are not entirely explained by crowding. Firstly, an inspection of Fig. 3A–E for the 0 abscissa, reveals a progressive decrease in letter recognition accuracy with increasing serial position for the complete report condition, specifically with pentagrams but not with trigrams for the same 0 abscissa value. Secondly, the progressive decrease in letter recognition accuracy with serial position within the pentagram sequence is confined to the complete report condition and not for the partial report condition. Given that positional uncertainty, acuity limitations, and arguably crowding is expected to have minimal effects on letter recognition accuracy at fixation (0 abscissa value in Figs. 2 and 3) for both trigrams and pentagrams,[18] therefore, the authors postulate that these observations are indicative of an interaction between memory (load and decay) and report accuracy. The following paragraph builds upon this postulation.

The lack of an effect of partial report on letter sequence recognition accuracy for trigrams, specifically at the fixation point, is not surprising as the number of characters that need to be reported are within the capacity limitations reported for visual short term memory (VSTM).[13] However, the number of characters that need to be reported in pentagrams exceed this capacity. Reports have suggested that visual memory comprises at least two components, a high capacity sensory memory that operates over very short durations (<100 ms) with a short decay period (~500 ms) and a limited capacity short-term memory which operates over longer duration exhibiting a slow decay over several seconds.[20] The capacity of the VSTM appears to be limited to a finite number of visual objects (approximately 3–4 characters in the case of letters).[13] Furthermore, the precision of stored information in VSTM decreases as the number of items required to be stored increases in number.[21] Cumulatively, these reports predict poorer report accuracy of letters in pentagrams as opposed to trigrams with complete report, and given that letters had to be reported in their correct sequence from left to right, it also supports the prediction that the latter serial positions in excess of 3 should be most affected by report condition. Both these predictions are consistent with the results obtained with partial report especially for the letter position at fixation.

Unlike the results described for the ''0'' letter position, the effect of partial report appears to affect both trigrams and pentagrams (albeit of larger magnitude for pentagrams) as viewing eccentricity increases. Furthermore, the increase in letter sequence recognition accuracy with partial report appears to increase progressively as viewing eccentricity also increases (Figs. 2 and 3). Additionally, this improvement is confined to the latter serial letter positions, i.e. serial position 3 in trigrams, and serial positions 4 and 5 in pentagrams. If positional uncertainty and crowding (excluding the limit of acuity as noted earlier) were the sole determinants of letter sequence recognition accuracy at these letter positions relative to fixation, then partial report should not have any effect at these letter positions because the stimulus configuration (within each string length) was similar in both report conditions. Given that the effect of partial report was confined to the latter letter positions in both trigrams and pentagrams (independent of its inner or outer position), the authors speculate that this observation is also consistent with the joint effects of memory (load and decay). Furthermore, we also believe there must be an additional process that exaggerates the effect of memory (load and decay) at these eccentric letter positions.

One candidate process that could account for the above result is additional delays imposed on memory encoding at these locations by the influence of crowding. We speculate that the increased magnitude (and extent) of crowding that occurs with increasing viewing eccentricity[18,19] may increase the perceptual processing time required to encode into memory the more crowded middle letters in trigrams and especially those of the pentagrams. Consequently, the increased processing time of letter elements imposed by crowding may increase the delay to relay this information to VSTM stores and invariably result in a cumulative increase of the delay to relay letter information in positions following the crowded target letter to VSTM stores as well. This will apply specifically for the complete report condition, which required subjects to report all letters in their correct sequence. In the partial report condition, the report accuracy of each letter is less affected by the time it takes to process the preceding letter in the series, thereby predicting an improvement in report accuracy of letters that are influenced by memory (load and decay), i.e. serial letter positions greater than about 3.

In an attempt to explore this postulation further, response times of key entries were also measured in 5 subjects for trigrams and pentagrams with the complete and partial report conditions. All experimental conditions were identical to that described in the methods section. Response time refers to the elapsed time (in seconds) from stimulus offset to a keypress. The internal timing function of Matlab was used to provide this measure. Table 2A and B lists the mean response times (±1 SEM) for only 3 letter positions relative to fixation (−6, 0, +6) according to report condition and the serial position of a letter within a trigram (A) or pentagram (B). A Two-way Repeated Measures ANOVA (Serial Position × Letter position relative to fixation) was conducted on the mean response times, and analyzed separately for complete and partial report for 5 subjects. In the case of the complete report, there was a significant main effect of serial position in trigrams ($F(2,44) = 93.408$, $p < 0.001$) and pentagrams ($F(4,74) = 89.981$, $p < 0.001$), with higher serial positions associated with longer response times following stimulus offset. This is expected given that letters in the complete report condition had to be entered in their correct sequence. There was no significant main effect of letter position for trigrams ($F(2,44) = 3.141$, $p = 0.098$) but a significant main effect of letter position for pentagrams ($F(2, 74) = 6.283$, $p = 0.023$). There was no significant interaction between serial position and letter position for trigrams ($F(4,44) = 0.257$, $p = 0.901$) and pentagrams ($F(8,74) = 2.119$, $p = 0.063$).

In the case of partial report with trigrams, there was no significant main effect of serial position ($F(2,44) = 3.041$, $p = 0.104$), but a significant main effect of letter position ($F(2,44) = 17.360$, $p = 0.001$) and a significant interaction

Table 2 (A and B) Mean response time in seconds (±1 SEM) for each serial position in trigrams (A) and pentagrams (B) for 3 letter positions relative to fixation (−6, 0, +6) separated according to report condition. Data are pooled across 5 subjects.

A

Letter position relative to fixation	Trigrams: mean (±1 SEM) response times (sec) by serial position		
	1	2	3
Partial report			
−6	0.779 (±0.091)	0.973 (±0.047)	0.902 (±0.056)
0	0.733 (±0.089)	0.829 (±0.062)	0.738 (±0.073)
6	0.812 (±0.094)	0.983 (±0.074)	0.778 (±0.095)
Complete report			
−6	0.985 (±0.097)	1.43 (±0.13)	1.678 (±0.142)
0	0.928 (±0.112)	1.261 (±0.122)	1.559 (±0.117)
6	0.966 (±0.099)	1.338 (±0.102)	1.597 (±0.118)

B

Letter position relative to fixation	Pentagrams: mean (±1 SEM) response times (sec) by serial position				
	1	2	3	4	5
Partial report					
−6	0.758 (±0.067)	1.038 (±0.080)	1.157 (±0.032)	1.036 (±0.082)	0.844 (±0.059)
0	0.755 (±0.063)	0.750 (±0.05)	0.884 (±0.072)	0.830 (±0.067)	0.731 (±0.091)
6	0.808 (±0.049)	1.009 (±0.070)	1.230 (±0.046)	1.039 (±0.072)	0.781 (±0.098)
Complete report					
−6	1.008 (±0.109)	1.249 (±0.088)	1.659 (±0.163)	2.102 (±0.214)	2.658 (±0.207)
0	1.016 (±0.104)	1.492 (±0.152)	1.984 (±0.181)	2.557 (±0.276)	2.685 (±0.215)
6	0.904 (±0.098)	1.306 (±0.121)	1.749 (±0.173)	2.058 (±0.248)	2.499 (±0.214)

effect between serial position and letter position ($F(4,44) = 4.918$, $p = 0.009$). Thus, letter positions at larger viewing eccentricities (−6 and +6) were associated with longer response times relative to the 0 letter position. This effect was due largely to the longer response times associated with letters occupying serial positions 2 and 3 in those letter positions (−6 and +6). In the case of partial report with pentagrams, there were significant main effect of serial position ($F(4,74) = 19.303$, $p < 0.001$), letter position ($F(2,74) = 17.549$, $p = 0.001$) and a significant interaction effect between serial position and letter position ($F(8,74) = 4.694$, $p < 0.001$). Thus, letter positions at larger viewing eccentricities (−6 and +6) were associated with longer response times relative to the 0 letter position. This effect was due largely to the longer response times associated with letters occupying serial positions 2, 3 and 4 in letter positions −6 and +6 compared to letter position 0.

In summary, the partial report response time data suggests that crowded letter elements (2 in trigrams, and 2, 3, 4 in pentagrams) displayed longer response times relative to their initial and final letters, furthermore, the response times for letters presented at these serial positions tended to increase progressively with increasing viewing eccentricity. This result is consistent with suggestions that perceptual processing may be slower for crowded letters compared to uncrowded letters.[22] Perhaps on a related note, the magnitude of crowding also seems to change systematically with stimulus duration, becoming larger in magnitude as stimulus duration is decreased progressively.[23] Interestingly, such an interaction also predicts slower processing time of letters presented in the peripheral visual field. Indeed, Lee et al.[24] reported slower lexical processing (discrimination of words from non-words) in peripheral vision, especially for low frequency-words and larger word lengths.

As mentioned earlier, the accuracy of recognition of the letter that is closest to fixation or the fovea (referred to as the inner letter), is usually much lower than the letter that is furthest from fixation (referred to as the outer letter).[2,7,14] The results presented in Fig. 4 provide clear evidence that the improvement in letter recognition accuracy associated with partial report depends on the serial position of the letters within the string of characters, and not on the inner/outer positions of the letters within trigrams, and more evidently in pentagrams. However, even with partial report, recognition accuracy for outer letters improved to near perfect performance but the same was not true for the inner letter even when it was the last letter within a string, i.e. letter recognition accuracy for inner letters remained significantly reduced specifically for peripheral locations, regardless of report condition and its serial position (Figs. 2 and 3). This result suggests that some factor other than memory decay exerts an additional limitation on recognition accuracy of inner letters. Again, it seems that crowding may be that additional factor. It has been reported that there exists an inner/outer anisotropy

with crowding, i.e. outer crowding targets (crowding stimuli located further from the fovea than the test target) are more effective crowding stimuli than inner crowding targets (crowding stimuli located closer to the fovea than the test target).[25] This interaction bears relevance to the trigrams and pentagrams used in the current study. The inner letter within a trigram or pentagram is flanked by letters which occupy outer positions within the string. Similarly, the outer letter within a trigram or pentagram is flanked by letters which occupy inner positions within the string. Therefore, it is conceivable that the inner/outer anisotropy reported with crowding may serve as a plausible candidate to account for the reduced letter recognition accuracy observed with inner letters within trigrams and pentagrams. If this is indeed the case, then it also explains why letter recognition accuracy for inner letters failed to exhibit complete improvement with partial report, specifically when presented at peripheral locations. Additionally, the effect of partial report appeared larger in the left hemi field compared to the right hemi field for both trigrams and pentagrams (specifically for the 3rd and 5th serial positions, respectively). The authors speculate that, given the right field advantage evident in the complete report condition (3rd and 5th serial positions in trigrams and pentagrams, respectively), it is conceivable that a fixed factor improvement in recognition accuracy across all letter positions with partial report, could manifest as a smaller gain in accuracy in the right hemi field due to response saturation at 100% accuracy, compared to the left hemi field.

Observation of a right hemi-field advantage reported in this study is consistent with several previous reports using random letter sequences[2,7,26] and words.[7,27] The exact reason for the hemi-field asymmetry noted with words and letters have received much debate resulting in 2 broad proposals to account for these perceptual asymmetries. The first proposal argues in favor of scanning habits that result from experience with reading,[27,28,29] while the second proposal argues in favor of cerebral hemispheric specialization (see[30] for a review). Evidence provided in favor of the first proposal include observations of a right hemi-field advantage (i.e. higher recognition accuracy) with English words, but a left hemi-field advantage with Yiddish words.[27] Similarly, the perceptual span (number of letters to the left and right of fixation which affect reading speed using a moving-window paradigm) is asymmetric, being larger on the right of fixation for English text,[31] but larger on the left of fixation when using Hebrew text[28] or Arabic text.[29] With regards to the second proposal, cumulative evidence suggests that the left cerebral hemi-sphere is more specialized for temporal, linguistic and cognitive processing, and the right hemisphere is more specialized for spatial processing (line orientation, Vernier offset and size discriminations).[30] Therefore visual stimuli requiring lexical and/or verbal processing are accomplished with greater efficiency (accuracy and response speed) in the right visual field than the left. However, there are also suggestions that attentional-driven mechanisms, which can be influenced by reading habits and cognitive demands, may modulate the hemi-field advantage despite hemispheric specialization, i.e. stimuli which usually display right visual dominance could shift to left visual field dominance, depending on the task required of subjects.[26,30,32]

Conclusions

In summary, the present study shows that letter sequence recognition accuracy is affected significantly by the number of characters comprising letter strings. Furthermore, letter recognition accuracy is intimately associated with processes involved in memory of letter elements, especially for the latter letters comprising letter strings. This effect becomes more pronounced as the number of characters comprising letter strings exceeds 2–3 characters. The results of this study bears particular relevance (albeit indirect) to the concept of visual span measures, as the latter are usually inferred from measures of letter sequence recognition accuracy.[2,3] While the influence of memory does seem to play a role in letter recognition accuracy with trigrams, this influence is rather small (~3%) on the overall area of letter recognition profiles, thereby suggesting a rather small effect on visual span measures. However, even though the effect of memory was arguably small for trigrams presented at foveal and para-foveal locations, the influence of memory becomes progressively larger with increasing viewing eccentricity even with trigrams, and particularly with pentagrams. Therefore, at this point, it remains unknown if the influence of memory (load, decay, and perhaps encoding) will have a much larger influence on letter recognition accuracy (and therefore visual spans) measured at larger retinal eccentricities relative to the fovea.

While it is not the intention of this study to support or refute the visual span hypothesis, nevertheless, it provides fairly convincing evidence that measures of letter sequence recognition accuracy are influenced by high-level memory factors (in addition to previous reports of crowding, positional uncertainty and visual acuity). Furthermore, these factors appear to play an increasing role as viewing eccentricity and string length increases. We also speculate that crowding not only affects letter recognition accuracy, but it may exacerbate the effect of memory factors, possibly due to additional delays it imposes on memory encoding.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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