# A VISUAL DISORDER PRODUCING HIGHLY SELECTIVE DELETION OF RECURRING LETTERS

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## Abstract

A case of unusually selective deletion of recurring letters is described. The disorder was primarily visual, spelling being unaffected. There was no evidence of neglect. Reading was fluent and rapid (not letter-by-letter), though words often appeared as a series of resolving fragments. Selective deletions were entirely confined to adjacent letters, excluding explanation in terms of repetition blindness (Kaniwisher, 1991). Mixing case and font, or increasing inter-letter distance, did not alter rate of recurring letter deletion, provided the task required some form of perceptual grouping. The final 2 experiments establish the pre-lexical nature of the deficit; they show deletion of recurring symbols, for example, when copying Navon-style global forms constructed from same or different Greek letters. This visual deficit is explained using the neural network model developed by Rolls and Deco (2002).

Key words: vision disorders, alexia, agnosia, attention

## INTRODUCTION

This report concerns a woman (TR) with an unusually selective tendency to delete recurring letters and/or same-letter gaps when reading. Miceli et al. (1995) previously described selective deletion of one doubled letter (e.g., *bloccare*  $\rightarrow$ *blocare*), but only spelling was affected, implying a lexical deficit "... at the level of the graphemic buffer ...". TR's deletions, which were even more selective, only affected reading; consequently, it is important to consider the possibility that her difficulty reflected a recognised form of peripheral dyslexia.

In neglect dyslexia, when reading a paragraph, the subject might omit words on the neglected side (most commonly the left side). They might omit (e.g., spine  $\rightarrow$  pine or ine) and/or substitute (e.g., spine  $\rightarrow$  brine or apine) and/or add (e.g., spine  $\rightarrow$ shrine) letters on the neglected side (Young et al., 1991). Patients with attentional dyslexia read single letters better than letters flanked by other letters (Shallice and Warrington, 1977). One model suggests reading individual letters in a string requires sequential restriction of an attentional "spotlight" to one letter at a time: inadequate narrowing of this attentional window causes intrusion errors, which (a) impair identification of a central target letter flanked by other letters, and (b) produces within- and/or between-string letter migrations (Mayall and Humphreys, 2000; Saffran and Coslett, 1996). Saffran and Coslett (1996) described an attentional dyslexic, NY, who frequently deleted doubled letters (e.g.,  $hoop \rightarrow$ hop). However, NY, and other attentional dyslexics (Hall et al., 2001) frequently generated other errors

(deletions, migrations, additions, and substitutions of non-recurring letters).

In letter-by-letter reading, subjects identify one letter at a time and latencies increase monotonically with word length. Letter-by-letter reading has been attributed to pre-lexical visual difficulties, including impaired activation of individual letters (Behrmann and Shallice, 1995), and a general deficit in the rapid visual identification of multiple symbols or pictures (Farah and Wallace, 1991). Moreover, for Farah (1990), ventral simultanagnosia reflects left occipito-temporal damage, which limits the number of objects that can be seen at any one time, yielding letter-by-letter reading. In contrast, in dorsal simultanagnosia, occipito-parietal damage restricts spatial attention and the spatial extent of contour that can be explicitly resolved at any one time. However, Humphreys and Price (1994) attributed simultanagnosia to poor feature discrimination in two cases, and argued that Farah's dichotomy does not explain all forms of simultanagnosia.

Though TR might be called simultanagnosic as objects and words appeared as a series of perceptual fragments, she read long words rapidly. Her error profile did not fit neglect or attentional dyslexia, and her selective same-symbol and gap deletions extended to non-lexical tasks. Accordingly, TR's difficulties are attributed to impaired ventral stream grouping and restriction of the number of form elements supportable in explicit visual percepts. The primarily visual nature of her deficit permitted explanation in terms of primate ventral stream neurophysiology and a recent biologically plausible model of visual object perception (Rolls and Deco, 2002).

Fig. 1 – Early CT scan, inset showing right hippocampalparahippocampal infarct.

## CASE REPORT

On 10.1.93, TR, aged 29 and predominantly right-handed, developed left-sided weakness and sensory impairment. These deficits resolved quickly leaving slight left-sided weakness and somatosensory loss. A CT scan performed on 11.1.93 revealed a small right hippocampalparahippocampal hypodensity due to a stroke (Figure 1). Visual fields were full to confrontation (acuity, J1 in both eyes). Neuropsychological testing on 16.6.93 found no evidence of visual neglect. However, she had topographical disorientation, marked prosopagnosia, and visual object agnosia for real and drawn objects. Semantic memory was markedly impaired; for example, she did not know the meaning of the word lion. She named 1/5 colours, but correctly matched colours (5/5). She made surface dyslexic and surface dysgraphic errors. Her fluent speech lacked obvious dysphasic errors. Autobiographical memory loss was extensive. A CT scan on 20.9.93 found slight prominence of the temporal horn of the right lateral ventricle. Her initial marked story and design recall deficits were relatively mild by 1994. WAIS-R Verbal IQ was 61 and 81, while Performance IQ was 68 and 87 in June 1993 and January 1994, respectively. Corresponding National Adult Reading Test (Nelson and Willison, 1991) scores increased from 4/50 to 32/50, the final score yielding a premorbid Full Scale IQ-estimate of 108. Repeat testing in August 1997 produced essentially the

same results. The Birmingham Object Recognition (Riddoch and Humphreys, 1993) Battery demonstrated late recovery of object recognition between 1995 and 1997: Association Matching (measuring semantic memory) scores increased from 20/30 to 28/30, corresponding Object Decision scores being 70/128 and 109/128 (both initial scores were impaired but final scores were not). However, figure-ground formation, as measured by the test of overlapping letters, geometric shapes, and objects, was similarly impaired at both assessments. For example, the ratio of naming latencies for adjacent: overlapping pairs of objects was above normal limits in the first (1:2) and second (1:1.7) assessments. She remained prosopagnosic throughout. All tests described subsequently were administered between 1995 and 1999.

TR persistently merged letters on either side of inter-word spaces if the same letter ended one word and began the next, when reading (e.g., were each  $\rightarrow$  wereach) but not when spelling to dictation. Similarly, TR correctly copied thirty 4- to 10-letter words lacking doubled letters (e.g., *importance*), incorrectly copying 15/30 words containing doubled letters solely through doubled letter deletions (e.g., *commission*  $\rightarrow$  *comission*): she correctly orally spelled all words to dictation.

Preliminary studies also investigated perceptions of briefly-exposed single and multiple letters and letter strings. After presentation of a central fixation square, 1 of 16 black on white lower case letters subtending  $0.9^{\circ}$  appeared  $2^{\circ}$  or  $4^{\circ}$  from fixation for 17, 51, 84, 118, or 152 msec on a computer monitor (VDU) in north (N), NE, E, SE, S, SW, W, or NW positions. TR identified significantly fewer letters (147/160) than one uninjured control subject (158/160) but not the other (151/160).

On disappearance of a fixation cross, 1.1° black lower case consonants, centred  $3.3^{\circ}$  to the right or left of fixation, were exposed against white for 17, 34, 68, 101, 135, or 168 msec on a VDU alone (N = 120), or flanked by letters – one at  $4.6^{\circ}$  or two at  $2^{\circ}$  and  $4.6^{\circ}$  from fixation. Trigrams (N = 120) comprised different letters (e.g., czq). Digrams were different-letter (N = 120; e.g., wn) or same-letter (N = 120; e.g., yy). Fully reported randomised stimuli appeared in counterbalanced monocular blocks. Excluding same-letter pairs, TR correctly identified letters 3.3° from fixation when these appeared singly (95%), in digrams (95%), or in trigrams (90.8%). Side of presentation ( $\chi^2_{df=1} = 0.42$ , NS), exposure duration ( $\chi^2_5 = 2.83$ , NS), and the number of letters presented ( $\chi^2_1 = 2.32$ , NS) did not affect performance. However, she was less accurate than 2 uninjured control subjects (single, 100% and 98.3%; digram, 99.2% and 95.8%; trigram, 97.5% and 98.3%). Scoring report of all letters as correct or incorrect produced identical results. Thus, TR processed different letters slightly less well than controls. However, full trigram report did not

require prolonged exposures and performance did not decline sharply with (a) increasing letter number (c.f., some simultanagnosic letter-by-letter readers Behrmann and Shallice, 1995; Levine and Calvanio, 1978) or (b) letter flanking (c.f., attentional dyslexia, Shallice and Warrington, 1977). Importantly, TR identified only 18.3% of same-letter digrams (69.2% deletions, e.g.,  $ww \rightarrow$ w; 12.5% visual, e.g.,  $ww \rightarrow wv$ ) – considerably fewer than controls (97.5% and 89.2%). Side did not affect TR's performance ( $\chi^2_1 = 0.89$ , NS), exposures longer than 101 msec being error-free.

## FURTHER EXPERIMENTAL INVESTIGATION EXPERIMENT 1

# Effects of Lexical Status and Spatial Distance on Deletion of Recurring Letters and/or the Intervening Gap

TR said written text was often incomprehensible because she merged words if the same letter ended the first and began the second (e.g., *the edge*  $\rightarrow$ *thedge*). This report distinguishes two types of adjacent recurring letters. Repeated letters are same identity letters straddling an inter-string gap (e.g., *the edge*, letters underlined to illustrate). Doubled letters recur within a string (e.g., *beer*).

The present study asks if TR selectively deletes doubled (e.g.,  $noon \rightarrow non$ ) as well as repeated letters and/or the separating gap (e.g., letter + gap, *reco ord*  $\rightarrow$  *record* and/or gap only, *reco ord*  $\rightarrow$ *recoord*). It also asks if letter and/or gap deletion rates vary with (a) lexical factors and (b) gap size and/or type.

## Method

There were nine stimulus sets, each containing 20 items. Sets 1-5 included an inter-string gap bounded by the same-letter (Sets 1-2) or differentletters (Sets 3-5). Set 1 gap deletion plus or minus letter deletion generated a nonword (e.g., ston ner  $\rightarrow$ stoner). Set 2 gap and letter deletion converted 2 nonwords into a word (e.g., sug gar  $\rightarrow$  sugar). Set 3, gap deletion converted two words into a word with at least one phoneme change (e.g., *fat her*  $\rightarrow$  *father*). Set 3 stimuli were reordered in Set 4 - merging produced a nonword (e.g., *her fat*  $\rightarrow$  *herfat*). Set 5 gap deletion yielded a word from a nonword and word (e.g., dra wing  $\rightarrow$  drawing). Set 6-9 items contained a doubled letter, with deletions altering phonemic structure: Set 6, nonword  $\rightarrow$  nonword (e.g.,  $noom \rightarrow nom$ ); Set 7, nonword  $\rightarrow$  word (e.g.,  $doog \rightarrow dog$ ; Set 8, word  $\rightarrow$  nonword (e.g.,  $door \rightarrow$ *dor*); and Set 9, word  $\rightarrow$  word (e.g., *steep*  $\rightarrow$  *step*).

Ten 10-lines, 45-item paragraphs were constructed from 450 items presented in random order, half of Set 1-9 items appearing in three paragraphs, the remainder in two. One further Set 1-5 item also straddled each line break, making 550 items and adding one "line" to each paragraph.

The following section from a paragraph starts and ends with Set 1-5 items straddling line break (alternate items italicised to illustrate). The items, in order, are from Sets 5 (*flow er*), 2, 8, 7, 1, 9, 1, 2, 3, 4, 6, and 2:

... flow er ques stion summer toon ase erp latter cag ger div vide not ice go bin fopper insta ance ...

A further 10 treble-spaced paragraphs were constructed by converting each single between- and within-item space into a 3-character space. Line breaks were doubled. Typographical errors excluded a few stimuli, these errors being duplicated in the treble-spaced paragraphs. TR read 4 blocks of 5 paragraphs, blocks 1 and 4 being single-spaced. The experimenter (E) rated TR's tape-recorded responses to identify clear interstring pauses. He also identified phoneme changes, signalling all Set 6-9 deletions (e.g., *noom*  $\rightarrow$  *nom*, *doog*  $\rightarrow$  *dog*) and some (e.g., *fam mous*  $\rightarrow$ *famous*), but not all (e.g., *seg gree*  $\rightarrow$  *segree* or *seggree*) Set 1-5 letter deletions.

In all experiments, statistical tests were twotailed, while nonwords were orthographically legal and phonologically plausible. Unless otherwise stated, lower black case 12-point Times New Roman or 10-point New Courier letters were used.

### Results

Set 1 and 2 inter-string gaps were almost always deleted in both gap size (single vs. treble spacing) conditions (Table I). Table I shows they were also usually deleted in both gap type conditions (i.e., character spaces vs. line breaks represent gaps). To ascertain whether TR deleted gaps and letters or only gaps, Table I considers instances where the phonemic structure of the stimulus was changed only if a letter was deleted as well as the gap (e.g., seco ond  $\rightarrow$  second). Apparently, she usually deleted letters and gaps, as the rate of phonemic change in Set 1 and 2 remained high in the type (character space vs. line break) and size (single vs. treble spaced) spacing conditions. As spacing factors did not alter deletion rate, subsequent analyses pool data from the type and size spacing conditions.

Deletions of gaps (Fisher Exact, p < 0.007) and repeated letters (signalled by phonemic change, Fisher Exact, p < 0.001) were slightly more frequent when they produced words (Set 2) rather than nonwords (Set 1). Table I pools results from Set 3-5 different-letter stimuli, which were virtually all pronounced as two strings. Set 1 and 2 vs. Set 3-5 contrasts were highly significant for gap deletion ( $\chi^2_1$  = 635.96, p < 0.001) and phonemic change ( $\chi^2_1$  = 488.30, p < 0.001).

		Single Spacing		Treble Spacing	
		Gap Deletion	Phonemic Change	Gap Deletion	Phonemic Change
Same Letter Gap					
Set 1 (ston ner $\rightarrow$ stoner)	Same line	41/46	14/18	45/46	15/18
	Line ends	18/19	6/7	19/19	6/7
Set 2 (sug gar $\rightarrow$ sugar)	Same line	47/47	31/31	47/47	31/31
	Line ends	19/19	13/13	19/19	13/13
Different Letter Gap					
Set 3 (fat her $\rightarrow$ father);	Same line	0/145	1/145	1/145	1/145
Set 4 (her fat $\rightarrow$ herfat);	Line ends	0/58	0/58	0/58	0/58
Set 5 (dra wing $\rightarrow$ drawing)					0.00

TABLE 1 Effect of Spacing Conditions (size and type) on Deletions of a Gap and/or Letter from Repeated or Doubled Letter Stimuli

Table II shows Set 6-9 letters were infrequently deleted (signalled by phonemic change). Indeed, letter deletions were considerably more frequent in Set 1 and 2 repeated letter strings than in Set 6-9 doubled letter stimuli ( $\chi^2_1 = 409.42$ , p < 0.001), suggesting that the gap separating recurring letters might facilitate deletion. Nevertheless, Set influenced double letter deletion rate (Kruskal-Wallis, p < 0.003), deletions being most common for nonword to word conversions (Set 7), and least frequent for the opposite conversion (Set 8).

TR rapidly read single-spaced (M = 72.4 sec, SD = 6.7) and treble-spaced (M = 70.7 sec, SD = 4.3) paragraphs, taking an average of 0.8 sec to read each (3- to 9-letter) string. In contrast to frequent recurring letter deletions, she made only 8 other errors (e.g., *hod*  $\rightarrow$  *hot*, *liveer*  $\rightarrow$  *livee*, and *know*  $\rightarrow$  *now*).

## Conclusions

1. This experiment confirmed TR's observation that she selectively deleted same-letter inter-string gaps. The high proportion of Set 1 and 2 phonemic change suggested that she often also deleted one of the same-identity letters bounding the gap.

2. Gap size (1 or 3 spaces) did not influence deletion rate. More importantly, same-letter deletions occurred when one letter ended a line and the other began the next line: consequently, TR's word/nonword groupings respected letter sequence, but not other topographical features.

3. Deletions were more frequent for nonword  $\rightarrow$  word conversions than for word  $\rightarrow$  nonword conversion, suggesting a slight lexical influence on deletion rate.

TABLE II Effect of Lexical Status on Doubled Letter Deletion Rate

	Phonemic Change
Set 6 (noom $\rightarrow$ nom)	3/100
Set 7 $(doog \rightarrow dog)$	10/94
Set 8 (door $\rightarrow$ dor)	0/100
Set 9 (steep $\rightarrow$ step)	4/100

4. She fluently read all strings. That is, she did not read letter-by-letter. There was no evidence of neglect or attentional dyslexia: she read all items, and she produced very few of the addition, substitution, or migration errors associated with these conditions (Hall et al., 2001; Young et al., 1991).

## EXPERIMENT 2

# Repetition Blindness cannot Explain Nonword Letter and Gap Deletion

Repetition blindness might explain recurring letter deletion. Thus, in sentences such as A brown dog came in in the house, the repeated in is missed. However, repetition blindness cannot explain selective same-letter deletion of inter-string **gaps**. Moreover, Kanwisher (1991) states that "... there is no repetition blindness for letters that are shared by two different words in a list (e.g., the t in fault and heart)." In contrast, TR deleted repeated letters (e.g., div vide  $\rightarrow$  divide) more often than doubled letters (e.g., spood  $\rightarrow$  spod) in Experiment 1.

Nevertheless, the differing deletion rates for doubled and repeated letters in Experiment 1 may have arisen because string lengths were not closely different matched in the stimulus Sets. Consequently, Experiment 2 asks if, as the repetition blindness hypothesis predicts, the repeated letter deletion rate is higher in singlestring stimuli such as burudde than in two-string stimuli comprising the same letters with a gap inserted between the doubled letters (e.g., burud de). Moreover, Bavelier and Potter (1992) showed that repeated letters were deleted more often when separated by 1 than by 2 symbols: i.e., reducing lag increases repeating letter deletions. Therefore, this experiment asks if repeating vowel are sometimes deleted (e.g., burude  $\rightarrow$  burde or sopone  $\rightarrow$  sopne).

Reading and oral spelling responses were compared. Reading aloud affords an immediate window into TR's visual percepts, but there is some latitude in the use of English phonemegrapheme correspondences. Subsequently, TR was asked to orally spell each target, as oral spellings are unambiguous. However, they introduce a delay between perception and production. To reduce the perception-production delay, TR's oral spellings were preceded by one probe question asking her if 1 or 2 graphemes represented the target consonant or vowel phoneme.

## Method

Set 1 stimuli were 16 nonword pairs. A repeating vowel separating 3 consonants made the first word. The final consonant followed by *e* made the second (e.g., *sunul le* and *sopon ne*). Removal of the gap generated Set 2 items (e.g., *sunulle* and *soponne*). Loss of a Set 2 doubled letter yielded Set 3 (e.g., *sunule* and *sopone*). For Set 4, the first Set 3 vowel was deleted (e.g., *snule* and *spone*). Stimuli were presented in sixteen lines, each containing one target from each set in counterbalanced order. Targets alternated with filler words in each line, e.g., (Set 3, 4, 1, and 2 targets italicised to illustrate):

# edge *sunule* bat *clage* tiger *balat te* lime *burudde* dagger.

TR read individually presented lines, the line being occluded immediately after she read the target of that trial. One question was then posed. Question 1 followed all targets and sought the number of final consonant letters: e.g., "How many b's in corobbe?". Question 2a determined recurring vowel number in Set 1 and 2 items: e.g., "How many o's in corobbe?". Question 2b solely aimed to distribute attention evenly across target letters; it asked about the number of letters representing Set 3 and 4 second consonants: e.g., "How many r's in crobe?". Finally, she orally spelt each target. All 16 lines were presented 4 times in 2 sessions. Each of the 64 items was the target once per session, Question 1 being asked in one session and Question 2 (a or b) in the other, question order being random and counterbalanced across sessions. Two Speech Therapists, blind to the stimulus, independently transcribed TR's tape-recorded responses to the target of each trial. They then agreed the most likely spelling of each response guided by their phonetic transcriptions and a written stimulus list, supplied with the misleading suggestion that it may contain distracters.

## Results

Raters independently transcribed all Set 1 utterances as a single nonword. Their phonetic transcriptions mostly concurred for vowel number (127/128) and identity (109/128) and for final consonant (126/128) identity. Table III presents data from raters' subsequently agreed spellings (NB: they did not agree 3 final consonants and 1 vowel number). The number of final consonant letters varied with Set ( $\chi^2_3 = 29.04$ , p < 0.001) because 2 letters most often represented the final consonants of all but Set 4 items. Data from the agreed spellings diverge from the repetition blindness hypothesis in that Set 1 repeated and Set 2 doubled letters were equally often deleted. Moreover, as indicated above, repetition blindness cannot explain why gaps were selectively deleted when reading Set 1 stimuli.

Probe responses agreed with subsequent oral spellings in all but 2 occasions: e.g., one probe response showed TR initially saw both *t*'s in *balat te*, while her subsequent oral spelling was *balate*. Table III presents oral spelling data. No Set 1 oral spelling contained a gap. One letter represented the final consonant of most Set 1, 3, and 4 (but not Set 2) items ( $\chi^2_3 = 76.87$ , p < 0.001). Against the repetition blindness hypothesis, Set 2 doubled letters were deleted less often than Set 1 repeated letters, the gap between the letters actually facilitating deletion (Table III). Moreover, in contrast to frequent repeated letter deletions, no Set 1-3 repeated vowels were deleted (Table III).

TR's spellings and those agreed by the raters concurred for (a) Set 1 inter-string gap deletion, and (b) vowel number. However, the rater spellings doubled Set 3 but not Set 4 final consonant letters. Presumably, TR applied different graphemephoneme correspondence rules when reading Set 3 and 4 items, the alternative explanation being improbable (i.e., she actually saw 2 final consonant

TABLE III

Incidence of Inter-string Gaps, Number of Vowels and Number of Final Consonants in Raters' Agreed Spellings and in TR's Oral Spellings of Set 1-4 Stimuli

	Set 1 (e.g., <i>balat te</i> )	Set 2 (e.g., <i>balatte</i> )	Set 3 (e.g., <i>balate</i> )	Set 4 (e.g., <i>blate</i> )
Raters' Agreed Spelling				
Gap (No. Absent: Present)	32:0	32:0	32:0	32:0
No. Final Consonants (1:2)	6:26	8:24	12:19	24:6
No. Vowels (1:2)	0:32	2:30	0:32	27:4
TR's Oral Spelling				
Gap (No. Absent: Present)	32:0	32:0	32:0	32:0
No. Final Consonants (1:2)	31:1	8:24	32:0	30:2
No. Vowels (1:2)	0:32	0:32	0:32	31:1

letters in Set 3 but not Set 4 items). Thus, TR's visual perceptions of Set 3 and 4 items are probably more accurately represented by her oral spellings than by rater agreed spellings. These considerations imply that her oral spellings also correctly indicate that she usually deleted 1 final consonant letter from Set 1 items. Finally, again in contrast to her frequent recurring letter deletions, TR produced only 6 other oral spelling errors: 2 phonological errors (e.g., *plide*  $\rightarrow$  *plied*), 2 single letter duplications (e.g., *stome*  $\rightarrow$  *stomme*), 1 addition, and 1 substitution.

## **Conclusions**

1. TR's visual percepts were more faithfully described by oral spelling than by phonetic transcriptions. Moreover, though the delay between perception and response is shorter for reading than for oral spelling, the neural representation of the final consonant only occasionally transformed over the delay. Consequently, subsequent experiments rely on copying.

2. The present results contradict 2 predictions of the repetition blindness hypothesis. First, withinstring Set 2 doubled letters should have been deleted more frequently than between-string Set 1 repeated letters. Instead, inter-string gaps facilitated repeated letter deletions. Second, repeated vowels were not deleted in oral spellings.

3. As in Experiment 1, TR did not read letter by letter. There was no evidence of neglect. Recurring letter deletion errors predominated in her oral spellings, which yielded little indication of the migration or other errors associated with attentional dyslexia.

## EXPERIMENT 3

# Mixing Font and Case does not alter Deletion Rate

Experiment 3 asks if TR only deletes physically identical shapes including letters. Alternatively, she may also delete abstract letter representations. More specifically, abstract letter identities would be deleted if TR deleted repeated letters from different-case and/or different font pairs. Alternatively, if she only deletes from same-case same-font pairs, then physical identity would be critical. In the latter case, deletion rate may decline as feature differences increase: i.e., deletion may be more common when same-letter features are similar (e.g., rr) than when they differ (e.g., gG).

#### Method

The 4- to 8-letter stimuli were generated from 12 words and 12 nonwords. Both sets included 2 examples with the letters l, n, e, d, g, and r doubled. A 2-character gap was next introduced

between doubled letters (e.g., din ner and stig ged). Letter and gap deletion generated another word from most (10/12) of the original words (e.g., spe  $ed \rightarrow$  sped), but not from nonwords. These 24 items were printed in 4 case-font combinations. All 4 combinations included lower case Times New Roman (Font<sub>1</sub>) letters. Font<sub>2</sub> (mostly Braggadocio) was selected to maximise shape differences, font size varying to ensure that all letters were roughly the same height. Combinations were: same case and font, all lower case Font, letters; different-case same-font, some upper case Font, letters; samecase different-font, some lower case Font<sub>2</sub> letters; and different-case different-font, some upper case Font, letters. Three mixtures were blocked. Here, the left segment of half of the stimuli (6 words and 6 nonwords) or the right segment of the other half were in lower case Font<sub>1</sub>, the remaining segments being in upper case and/or Font<sub>2</sub> (e.g., bar RED, **Dar red**, and **bar RED**). Font<sub>1</sub> lower case letters also alternated with upper case and/or Font, letters (e.g., bAr ReD, Dar red, and bAr ReD). These 7 conditions (same case and font plus the blocked and alternate mixes) generated 168 stimuli. Selected segments of these 168 items were combined to produce 32 control items with different-letter gaps (e.g., star **IoW**): a typographic error necessitated deletion of one of these. The 199 stimuli were individually presented in pseudorandom order for TR to pronounce then to copy, a slash representing inter-string gaps.

## Results and Discussion

Table IV shows TR deleted few control different-letter gaps and almost all same-letter gaps  $(\chi^2_7 = 133.22, p < 0.001)$ . Moreover, different letters were never deleted, while a recurring letter was frequently deleted  $(\chi^2_7 = 29.21, p < 0.001)$ , the deletion rate being constant across case-font conditions. The E categorised mixed case-font target letters as almost identical (e.g., **Dar** red), similar (e.g., BeL low), or very different (e.g., lad

TABLE IV Frequency of Gap and Letter Deletions: Manipulating the Casefont Mix does not alter Selective Deletion Rate

	Deletion Incidence		
	Gap	Letter	
Same case			
Same font	24/24	12/24	
Different font			
Blocked	23/24	14/24	
Alternate	23/24	14/24	
Different case			
Same font			
Blocked	23/24	11/24	
Alternate	23/24	10/24	
Different font			
Blocked	23/24	11/24	
Alternate	22/24	12/24	
Control			
Different letters	2/31	0/31	

**DY**). Letter deletions were equally frequent in all 3 levels of shape similarity ( $\chi^2_2 = 0.32$ , NS). TR's only other errors were 6, probably phonological, single letter substitutions. Table IV treats all 6 substitutions as correct because she made a single substitution in the different-letter control condition and in 5 experimental conditions (all 5 being, *dor*  $re \rightarrow doore$ ).

As in Experiments 1 and 2, TR quickly read each stimulus aloud: i.e., reading was not letter by letter. Migration errors of attentional dyslexia are not confined to repeated letter deletions. TR's deletions affected central letters, ruling out neglect.

In summary, selective gap and letter deletion rates were comparable across same-letter conditions, similar (e.g., r r) and different (e.g., g r) letterforms being equally vulnerable. It is concluded that TR deleted abstract letter identities.

### **EXPERIMENT 4**

# Deletion and Fragmentation in Nonwords

Experiment 4 replicates evidence that differentcase repeated and doubled letters were deleted. It further shows that she did not delete adjacent similarly-shaped different-identity letters. This study also confirms preliminary data showing that TR only deleted single letters, not recurring lettersequences (e.g., she did not make errors such as  $slor ort \rightarrow slort$ ).

## Method

The first stimulus set comprised twenty-four lower case 9-letter nonwords, which included left (e.g., *irrasteat*), middle (e.g., *inoddaist*), or right (e.g., *doscrippe*) doubled letters. Changes to each of these first set items generated 7 further 24-item stimulus sets. In an upper case set, an upper case letter substituted one lower case doubled letter (e.g., *irrasteat*  $\rightarrow$  *iRrasteat*). A 2-recurring-letter set was produced by converting the doubled and immediately adjacent letters into a repeated 2-letter sequence (e.g., *irrasteat*  $\rightarrow$  *iristeat*). In the shape control set, a similar-feature letter (*p*, *r*, *d*, *o*  $\rightarrow$  *q*, *n*, *b*, *e*, respectively) substituted one doubled letter (e.g., *irrasteat*  $\rightarrow i\underline{nr}asteat$ ). Insertion of a space between the target letters of the items of the first 4 sets generated a further 4 sets (e.g., *ir rasteat*, *iR rasteat*, *ir irsteat*, and *in rasteat*). One typographical error reallocated a stimulus into another set, and the other error necessitated removal of that item. Stimuli were presented individually and in random order. TR read each aloud before transcribing it, representing interstring gaps with a hyphen.

### Results

For with-gap strings, 1 gap was deleted (Table V), no gaps were added, and 6 were relocated up to two letters to the left (e.g., *spetrale*  $e \rightarrow spetra-le$ ) or right.

For the 4 sets of without-gap stimuli, gaps were inserted into between 16.7% and 33.3% items. For those containing doubled letters, inserted gaps were significantly (Binomial p < 0.007) more often located between doubled letters (e.g., *deloffots*  $\rightarrow$ *delof-ots*) than off-target. The gap was inserted between the target letters of 2-recurring-letter and control strings, (e.g., *spetralal*  $\rightarrow$  *spetral-al*, target letters underlined) as often as not (Binomial, NS): all off-target gaps appeared towards the centre of strings with left-sided targets (N = 7, e.g., *coesleats*  $\rightarrow$  *coes-leats*) or right-sided targets (N = 8, e.g., *cirostees*  $\rightarrow$  *ciros-tees*).

The 6 target letter substitutions (e.g., *ase<u>nanate</u>*  $\rightarrow$  *ase<u>nenate</u>*) were ignored, being evenly distributed across conditions. Considering target deletions, complete 2-recurring-letter sequences were never deleted, though there were occasional single-letter errors (e.g., *ir irsteat*  $\rightarrow$  *ir-isteat*). Letter deletion rates were comparable whether case was mixed or unmixed within the repeated and doubled subgroups (Table V), so mixed and unmixed case data were pooled. Repeated letters ( $\chi^2_1 = 60.92$ , p < 0.001) and doubled letters ( $\chi^2_1 = 21.60$ , p < 0.001) were deleted more often than shape control letters with and without gaps, respectively (Table V). Moreover, letter deletions were more common ( $\chi^2_1 = 18.48$ , p < 0.001) in repeated than in doubled targets (Table V).

TABLE V
Number of Gaps Perceived and Target-letters Deleted in Nonwords with rRepeated or Doubled Letters

Stimuli	0	Gap		Letter Deletion	
(with-gap examples in brackets)	With Gap (Deletion)	Without Gap (Insertion)	With Gap	Without Gap	
Lower case recurring	0/25	7/24	23/25	13/24	
(e.g., <i>inod daist</i> ) Mixed case recurring (e.g., <i>uN niposta</i> )	1/24	6/24	23/24	14/24	
2-recurring-letter	0/22	8/24	2/22	0/24	
(e.g., <i>esporot ot</i> ) Shape control (e.g., <i>nevar neal</i> )	0/24	4/24	0/24	0/24	

Off-target letter errors were mostly phonological and were equally distributed across conditions: 12 single-letter additions (e.g., preorasin  $\rightarrow$  preoraisin), 3 one or two letter substitutions (e.g., cunslot  $ta \rightarrow conslot ta$ ), 1 deletion (i.e., meargar ar  $\rightarrow$  meagar ar), and 1 migration (i.e.,  $nevar-\underline{arel} \rightarrow nevar-\underline{eal}$ ). Comparing the 4 leftmost vs. 4 rightmost letters, off-target errors were more frequent on the right  $(\chi^2_1 = 4.35, p < 0.05)$  perhaps because nonwords are transcribed left-to-right yielding more rightsided phonological errors for long nonwords. More importantly, left and right target rates were very similar ( $\chi^2_1$  = 0.00, NS); i.e., unilateral neglect does not explain target letter deletions.

## Discussion

TR's deletion of different-case recurring letters and faithful transcriptions of similar-feature (different-letter) control pairs confirms that abstract letter identities are deleted. The lateral reach of this effect did not extend beyond adjacent single letters, as 2-recurring-letter sequences were not deleted. It is suggested that competitive lateral interactions between adjacent same-identity letter representations weaken or "delete" one letter representation but not letter sequences, especially as she selectively deleted recurrent letters exposed too briefly for saccade initiation (see Case Report).

In the present study, TR added gaps, while the other 5 studies in this report demonstrate robust gap deletion. This difference is explained using 3 assumptions. First, gap additions reflect TR's fragmented perceptions. Thus, she said that she often read short letter strings as fully resolved single units, but longer strings first appeared as an indistinct dark blur, which sometimes included uncategorized forms. The blur then subdivided into 2 or  $\overline{3}$  segments separated by "illusory" gaps, which she distinguished from real spaces. The letterforms in 1 segment then resolved. Subjectively, this process entailed matching letters with candidate phoneme sequences. The segment then returned to its blurred state as the next segment resolved, the process repeating itself for any third fragment. Finally, she mapped the sounds of phoneme groups onto their remembered locations in the residuum of the initial visual representation of the whole string.

It is next assumed that she sometimes confused illusory and real gaps. On one hand, same-letter real and illusory gaps were particularly difficult to distinguish because competitive lateral interactions are particularly strong when adjacent letters are the same. One letter representation might be weakened or "deleted". A weaker signal in the region of doubled letters may have contributed to TR's present tendency to insert a gap between doubled letters in unbroken strings. On the other hand, while Experiments 1-3 indicate that TR most readily distinguished real from illusory gaps separating different letters, the present addition of gaps to unbroken control strings suggests she sometimes converted illusory into real differentletter gaps when resolving longer nonwords.

The third assumption is that resolved fragments were short because TR could group only a severely limited amount of information in one visual percept. Remembering phoneme sequences and remapping them onto a residual visual representation of the string creates more room for information degradation and error. It is argued that TR degraded (and, consequently, deleted) gap information in the attempt to "squeeze" the shorter strings of Experiments 1-3 into a single object grouping. Conversely, representations of potential inter-string spaces were facilitated in the pressure to encode long 9-letter strings into at least 2 visual percepts; consequently, TR introduced rather than deleted gaps in the present study.

Finally, fragmentation might facilitate recurring letter deletion. In the complex process of segment resolution, it might be difficult to distinguish (a) "erroneous" re-activation of a letter in a previously-resolved segment from (b) an adjacent identical letter in another segment. Additionally, insertion of a gap between recurring letters might enhance deletion because gaps trigger saccades, necessitating integration of new visual input with that gained from the previous saccade. This might increase the difficulty of distinguishing single and adjacent recurring letters.

## EXPERIMENT 5

## Non-lexical Symbol Groups are Deleted

Experiment 5 eliminates lexical influences, which conceivably constrained letter and gap deletions in Experiments 1-4. It demonstrates selective same-symbol gap deletion from meaningless strings of English consonants, Greek letters, and mathematical symbols.

## Method

Insertion of 4 line breaks into 8 randomlysequenced, 144 lower case consonant (c, r, n, and x) strings yielded 5 different-length lines. "Paragraphs" of variable length letter groups were created by inserting inter-string spaces at random points within each line: 117 spaces (39 spaces 1, 2, and 3 additional characters wide) were distributed between 8 different "paragraphs" which contained 11-19 spaces. Four versions of the 8 paragraphs were created: same or different letters bounded all (a) inter-string gaps and/or (b) line breaks. Mathematical symbols (-, +,  $\approx$ ,  $\div$ ) or Greek letters ( $\phi$ ,  $\sigma$ ,  $\pi$ ,  $\tau$ ) were substituted for each letter to produce 2 further 32-paragraph sets. The following 2 lines are from a different-symbol inter-string gap, same-symbol line break, Greek-letter paragraph:

# φπφσφτ φπτσπστ σφσ πσπσττσφ τπσφσττ φτπτπτ τφσπφπτφσστ πσττπσσπσ φτππσφπφσφ

TR counted either symbol groups/strings or inter-string gaps. Line breaks were included in group counts, and excluded in gap counts (the above lines contain 9 symbol groups and 7 gaps). Two 2 matched and randomly ordered 48paragraph blocks were presented in the same order in 2 sessions. In session 1, TR counted groups and gaps in the first and second blocks, respectively. In session 2, gap counting preceded group counting.

#### Results

Group counts (M = 18.5 sec, SD = 4.3, per paragraph) took longer (t = 8.27, p < 0.001) than gap counts (M = 13.2 sec, SD = 4.5). Proportion correct (group count divided by correct group number) was the dependent variable in a  $3 \times 2 \times 2$ ANOVA with symbol (English vs. mathematical vs. Greek), gap (same- vs. different-symbol), and line break (same- vs. different-symbol) as factors. Gap [F (1, 84) = 9240.09, p < 0.001] and break [F (1, 84) = 9240.09, p < 0.001]84) = 694.89, p < 0.001] were the only significant terms because TR identified virtually all differentsymbol (3 gap sizes and line breaks) boundaries, and remarkably few same-symbol boundaries (Table VI). Thus, her group counts were close to the true value when all separations were differentletter. There were 4 line breaks, and she deleted about 4 groups from same-symbol-break, differentsymbol-gap paragraphs. Conversely, each line in same-symbol-gap, different-symbol-break paragraphs was usually deemed a single group. She often saw only one group when gaps and line breaks were both same-symbol.

TR missed an average of 4.9 (SD = 2.2) gaps (Table VI). Her gap count divided by the true gap number was the dependent variable in a  $3 \times 2 \times 2$ ANOVA with symbol, gap, and break as factors. Symbol was significant [F (2, 84) = 3.10, p < 0.05] because she saw more (M = 1.2) consonant than mathematical symbol gaps. Gap approached significance [F (1, 84) = 3.56, p < 0.07] because she detected slightly more different-letter gaps than same-letter gaps. However, break [F (1, 84) = 0.01, NS] and all other terms were insignificant.

## Discussion

When grouping symbols, TR selectively deleted same-symbol spaces. This clearly non-lexical deficit affected all symbols equally. In contrast, same-symbol gaps minimally impeded gap counting.

TR described different group and gap counting strategies. For group counting, she said she combined each successive symbol with the previous few symbols until a break appeared. She then (a) added 1 to the cumulating group count, and (b) started assembling the next group. This strategy narrowly focused on local features. However, gap counting was more global: she said, "I keep looking for a white gap and then I become aware of the letters." Here, her apparently more global analysis might have reduced detection of smaller gaps (about 5 per paragraph), but her global strategy did not entirely eliminate local analysis, since there was a weak tendency to delete same-letter gaps.

A spontaneous comment fits the foregoing local-global hypothesis rather well. After counting 1 group in a same-letter (gap and line break) paragraph, TR pondered, "I say 'one' but it's four lines ... but it's all one group? When you took it away, it flashed that it was four lines." More specifically, her group counting focus was local and confined to a few symbols: she counted 1 group because no clear break appeared (though she probably perceived "illusory" gaps) despite large eye movements at line breaks. In contrast, she adopted a global perspective when the paragraph was removed and she discerned 4 of the 5 lines. This fits another comment that she often initially perceived the 5-line paragraphs as a top and a bottom line of dark blurred segments each separate from a blurred region sandwiched between these lines.

TABLE VI	
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Mean Number of Groups (true M = 19.6) and Gaps (true M = 14.6) counted in Paragraphs Composed of Different Symbols and Gap Types (number deleted in brackets)

	DIFFERENT SYMBOL GAPS Line break symbols		SAME SYMBOL GAPS Line break symbols	
	Different	Same	Different	Same
1. Count Groups English letters Greek letters Math symbols	19.1 (- 0.5) 19.4 (- 0.2) 18.9 (- 0.7)	15.4 (- 4.2) 15.5 (- 4.1) 15.3 (- 4.3)	5.1 (- 14.5) 5.0 (- 14.6) 5.3 (- 14.3)	1.0 (- 18.6) 1.5 (- 18.1) 1.4 (- 18.2)
2. Count Gaps English letters Greek letters Math symbols	11.5 (- 3.1) 10.0 (- 4.6) 9.1 (- 5.5)	10.4 (- 4.2) 9.9 (- 4.7) 9.8 (- 4.8)	9.5 (- 5.1) 9.5 (- 5.1) 8.8 (- 5.8)	9.8 (- 4.8) 8.8 (- 5.8) 8.8 (- 5.8)

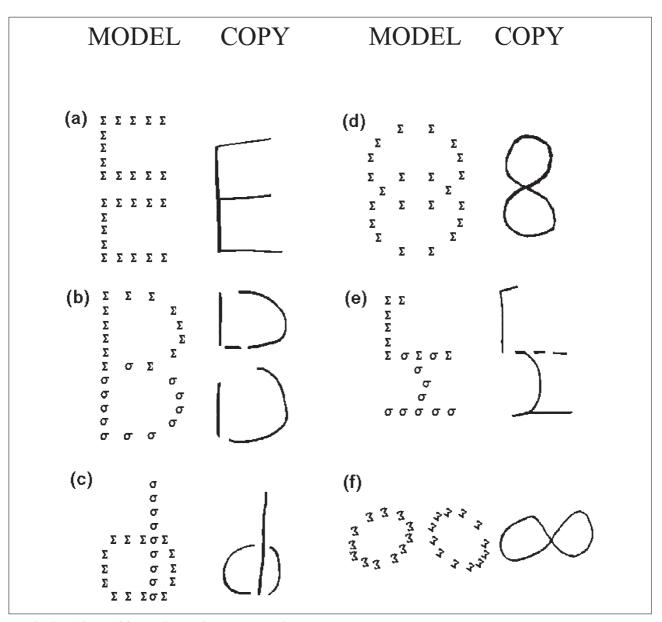


Fig. 2 – Selective deletion of same-element Navon-style contours.

## **EXPERIMENT 6**

# Non-lexical Navon-style Contours are also Deleted

Experiment 5 demonstrated deletions of gaps separating non-lexical symbol groups that could not be phonologically encoded. That observation is extended here with Navon-style forms, which reveal selective deletion of same-Greek-letter contours and gaps. An initial formal study used pairs of familiar forms that (a) were separated by a gap, (b) shared one contour, or (c) overlapped. Subsequent supplementary explorations probed this phenomenon further.

#### Method

There were 4 pairs of meaningful forms, each constructed from the same (e.g., Figure 2a and d) or different (e.g., Figures 2b and c) Greek letter ( $\Sigma$  and

σ). Model forms were separated by a gap (e.g., Figure 2a), shared a contour (e.g., Figure 2b), or overlapped (e.g., Figures 2c and d). The pairs were: vertically arranged C-shapes, contour and gap deletion producing an E (e.g., Figure 1a); vertically arranged D's (see Figure 2b), contour and gap deletion yielding B; adjacent 0 l (see Figure 2c), producing d on contour and gap deletion; and vertically arranged O's (see Figure 2d), forming 8 after contour and gap deletion. These randomly ordered 24 stimuli, which were 2.5 cm to 4 cm high and 1.6 cm to 2.3 cm wide, were presented individually for 10 sec and drawn from memory. They were continuously exposed and copied later on. Supplementary investigations relied on direct copying.

#### Results

Table VII shows that TR usually deleted a contour and gap from separate (e.g., Figure 2a) and

	Same Elements		Different Elements	
	Contour	Contour	Contour	Contour
	Deletion	Continuity	Deletion	Continuity
Separate contours	4/4	4/4	0/4	4/4
Shared contour	0/4	4/4	0/4	0/4
Overlapping contours	3/4	4/4	0/4	0/4

TABLE VII Meaningful Navon-style Greek-letter Contours: Frequency of Contour Deletion and Continuity

overlapping (e.g., Figure 2d) same-Greek-letter pairs, but never from different-letter pairs (e.g., Figure 2c). Unsurprisingly, contours were never deleted from shared contour pairs (Figure 2b). Table VII also shows that same-letter forms were always drawn as continuous and without breaks (Figures 2a and d). Different-letter forms were continuous only for separate pairs (Table VII), and breaks in her copies of shared and overlapping contours often corresponded with the points of transition from one letter to the other, presumably reflecting lateral inhibition between competing forms and/or groupings (see Figures 2b and c). Finally, identical results were obtained when TR copied from continuously exposed models.

Four pairs of nonsense forms were constructed from the same or different Greek letters (e.g., Figure 2e). Separate and shared contour versions were created. TR's copies of these 16 continuously exposed stimuli corresponded with her copies of meaningful forms. Separate same-letter contours merged and contours were continuous. Differentletter nonsense contours or the intervening spaces were never deleted and shared contours were discontinuous (Figure 2e).

The distance between the meaningful forms of original separate contour stimuli was doubled (4 mm to 8 mm). Whole stimuli were doubled in size on another occasion. These size manipulations did not reduce selective deletion of same-letter contours.

The 4 separate contour pairs and a fifth (V V  $\rightarrow$  W, adjacent V-shapes becoming a W-shape, if merged) were constructed from various elements. These were sometimes presented on more than one occasion. She consistently merged only same-letter contours. Her robustly selective same-letter deletions extended to the following component elements: English letters (10/10), dots (9/10), asterisks (10/10), and dashes (5/5). This effect also generalised to contour pairs both constructed from the letter  $\Sigma$ , with the letter elements rotated through 180° (which usually, 9/10, merged) and 45° (which often, 5/8, merged, Figure 2f).

There were limits to these effects. Thus,  $90^{\circ}$  Greek-letter element rotations infrequently (2/12) merged. Merging did not occur when contours were continuous unbroken lines (0/5), suggesting that grouping discrete elements into a contour facilitated merging. Finally, 5 contour pairs constructed from dots were presented with one set

of the pair coloured red, the other dots being blue. Five similar mixed colour pairs were constructed with dashes. TR rarely merged these contours (1/10), indicating that colour or form differences in the grouped elements prevent deletion.

Finally, TR sometimes described her perceptions. After drawing Figure 2c, she said, "It's like a blur if I look at it all at once", and "I home in on the biggest part first..." She added that she saw the left-sided arc first, then the vertical line and, finally, the right-sided arc. In fact, when asked, she always saw different-symbol forms as a series of resolving fragments, while all parts of same-letter stimuli appeared simultaneously in an unfragmented percept.

## **Conclusions**

1. Selective same-symbol deletions extended to meaningful and meaningless Navon-style global forms, emphasising the non-lexical nature of the deficit. Moreover, merging of vertically arranged components tends to suggest that neglect cannot explain her difficulty.

2. TR deleted contours made from various elements (English and Greek letters, dots, asterisks, and dashes), which further suggests a non-lexical grouping disorder.

3. Greek letters were used in the belief that they would evoke neural shape representations rather than abstract letter identities. However, she deleted the same Greek letters rotated through  $45^{\circ}$  or  $180^{\circ}$ , and she recalled using Greek letters in school algebra; consequently, Greek letters may have evoked some form of abstract representation. It would, therefore, be interesting to see if deletions extend to Navon-style forms composed of completely unfamiliar shapes (e.g., Arabic letters), as that would indicate that shapes per se (i.e., relatively low-level feature combinations) can support deletion.

4. The fragmentation TR experienced during word resolution extended to Navon-style global forms. Some stimuli were fragmented into 2-3 parts; each was resolved individually as the other segment(s) remained blurred.

### GENERAL DISCUSSION

Experiments 1-4 demonstrate robust selective deletion of recurring letters and/or associated gaps.

This effect was limited to adjacent single letters, as recurring 2-letter sequences (e.g.,  $arar \rightarrow arar$ ) were unaffected in Experiment 4. Experiment 2 excluded repetition blindness as a possible cause (Kaniwisher, 1991). In Experiments 2&4, the gap between repeated letters facilitated deletion (doubled letters being less often deleted), and this effect was linked with TR's tendency to resolve letter-strings as a series of fragments. Robust deletions from case and font mixtures (e.g.,  $d\mathbf{D} \rightarrow d$ ) and no effect of letter shape similarity on deletion (e.g.,  $pq \rightarrow pq$ ) show she deleted abstract letter identities (Experiments 3 and 4). Experiments 5 and 6 confirm the deficit was nonlexical. Thus, same-symbols (e.g., Mathematical symbols and Greek letters) were selectively deleted when TR (a) assembled symbols into non-linguistic groups and (b) copied meaningful and meaningless Navon-style global forms.

Selective recurring letter deletions and the virtual absence of substitution and migration errors excluded explanation in terms of attentional dyslexia. There was no evidence of neglect and she did not read letter-by-letter. Moreover, the visual non-lexical nature of TR's reading difficulties permits the present attempt to link TR's deficits with primate visual neurophysiology and the biologically plausible neural network model developed by Rolls and Deco (2002).

# Implications of the Rolls and Deco (2002) Model for Reading

Single cell recordings reveal steadily increasing receptive field (RF) area as the signal feeds forward through V1  $\rightarrow$  V2  $\rightarrow$  V4  $\rightarrow$  TEO (posterior inferotemporal)  $\rightarrow$  TE (inferotemporal) cortices. Figure 3 schematises the increasing receptive field size in ventral visual pathways. It shows lateral geniculate body innervation of V1 RF1 to RF8. Projections from two V1 neurons (RF1 and 2) converge onto one V2 neuron, yielding a double-sized RF. Similarly, the left-most V4/TEO neuron receives information from V1 RF's 1-4, while the TE neuron is informed by RF's 1 to N. Thus, if a stimulus activating V1 RF1 moves (or if the eyes move) so that RF2 is now activated, then the same V2 and all subsequent neurons still respond to that stimulus. Similarly, stimulus movement to RF3 causes selective activation of the next-in-line V2 neuron, but the same V4/TEO and TE neurons still respond to that stimulus. VisNet simulated this translation invariant effect for the symbols L, T, and + (Rolls and Deco, 2002). Each symbol activated nodes in a circumscribed region of input layer 1, while layer 4 nodes responded wherever the symbol was located. Rolls and Deco (2002) also report the following actual progression in RF size in the macaque: V1  $(0.5^{\circ}) \rightarrow$  V2  $(3.2^{\circ})$  $\rightarrow$  V4 (8°)  $\rightarrow$  TEO (20°)  $\rightarrow$  TE (40°). The progressive coarsening of the spatially discrete

retinotopic organisation of V1 until its apparent loss in TE (where cells respond to stimuli appearing in central vision) corresponds with increasing complexity of the forms evoking selective neuronal responses. Thus, V1 neurons respond selectively to oriented edges, while some TE neurons respond to faces (Desimone et al., 1985; Hasselmo et al., 1989). At intermediate stages, the proportion of cells responding to complex feature combinations increases as the signal passes through V4 to TEO (Tanaka et al., 1993).

In addition to feeding forward, extensive backprojections feed the signal back. The resulting re-entrant recycling of information presumably partly underlies prolongation (200-300 msec) of TE neuronal responses (Rolls and Tovee, 1994). Importantly, monkeys successfully discriminated backwardly masked faces, though TE neurons were selectively responsive for only 20-30 msec, which suggests that the early activity phase is often sufficient for identification. Later phases of the sustained TE activity may correlate with other processes such as short-term visual memory (Rolls et al., 1999) and/or may contribute to recognition of ambiguous objects. Consider a possible implication for visual representations of ambiguous objects. One form of ambiguity might entail insufficient activation of a single TE neuronal ensemble selectively tuned to the stimulus. Response selection often does not proceed until one ensemble attains supra-threshold activation via recycling activity in striate-extrastriate circuits. The hypothesised dynamic recycling of information would presumably include activity in nonretinotopic TE neurons plus increasingly retinotopic activity as backprojections re-activate TEO, V4, V2, and perhaps V1. Thus, the ambiguous representation is a dynamic spatially distributed zone of activity. It includes responses to (a) simple features in neurons within a defined region of retinotopic primary cortex, (b) more coarsely retinotopic intermediate cortical (V4/TEO)representations of complex feature combinations, and (c) non-retinotopic activity in TE neurons tuned to different objects.

Covert attentional shifts might resolve the ambiguity through sequential and more detailed analyses of different parts of the ambiguous object; Rolls and Deco (2002) provide a neural mechanism that may have been engaged when TR sequentially resolved perceptual fragments. They suggest parietal projections to V1 (and possibly up to V4/TEO) selectively facilitate activity in discrete retinotopic regions of vision (Figure 3). Here, modulation would act on the retinotopic end of the TE) dynamic recycling (V1 through to representation of the ambiguous object. This attentional activation is effectively equivalent to allowing only a spatially limited segment of the stimulus to be fed forward, thereby allowing

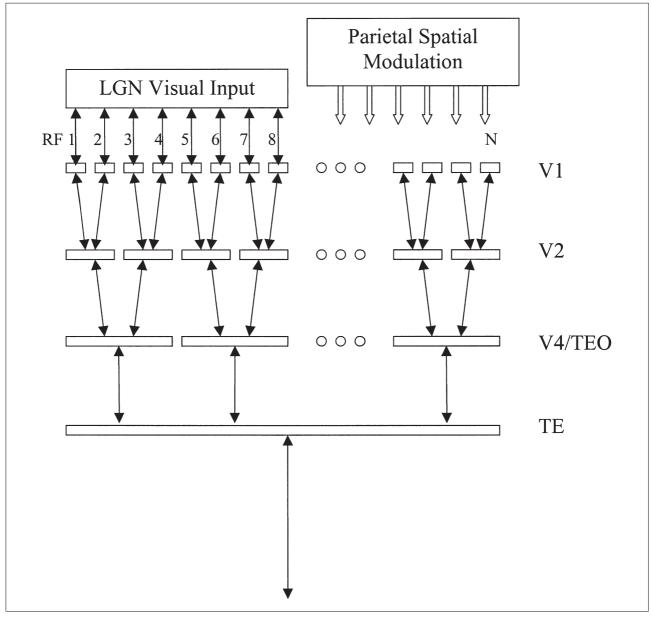


Fig. 3 – Ventral stream retinotopic through to non-retinotopic cortical substrate for recycling visual representations modulated by dorsal stream parietal spatial attentional processes.

"later" extrastriate networks to predominantly process that segment. Once that part of the signal has been processed, parietal modulations would highlight another zone. These sequential attentional shifts might glean sufficient information for suprathreshold activation of one TE, object-specific, neuronal ensemble.

## Extension of the Model to TR's Reading

This will be achieved using the model Caramazza and Hillis (1990) applied to a case of neglect in lexical and non-lexical tasks. The model specifies 3 stages preceding access to the orthographic input lexicon. In stage 1, feature contours (e.g., horizontal and vertical lines) are represented retinotopically. In stage 2, features are integrated into letter shapes – the physical appearance of letters being maintained (e.g., R, r, and  $\Re$  being distinct). In stage 3, graphemes are computed from letter shapes. These abstract letter identities (case- and font-independent) are stimulus-centred, being spatially arrayed according to ordinal positions relative to the central letter (e.g., in *CUP*, *<C>*, *<U>*, and *<P>* occupy positions – 1, 0, and 1, respectively).

It is suggested that V1 (and perhaps V2) provide a retino-centric feature map of letter strings, while neurons responding to letter shape and abstract letter identities are in the human homologues of intermediate ventral extrastriate regions (V4/TEO). However, relatively more V4 (and perhaps V2) neurons respond to shape, while TEO neurons are more often tuned to abstract letter identities (Tanaka et al., 1993). V4 and TEO are coarsely retinotopically-organised; consequently, activated abstract letter identities would coarsely

encode within-string left-right location. This model diverges from the original in 3 ways. First, retinotopy ends after stage 1 in the original. In the present account, it progressively degrades from V1 through TEO, which affords a stimulus-centred representation by gathering information from a large number of V1 neurons. Second, Caramazza and Hillis (1990) specify solely bottom-up processing, but this assumption is biologically implausible, given the evidence of extensive backprojections and recycling of neural activity between visual cortices (Rolls and Deco, 2002). Moreover, the modified model resolves a puzzle recognised by Caramazza and Hillis, who could not reconcile 2 assumptions: graphemic information is (a) abstract and it is (b) "... arrayed in a spatially defined co-ordinate system." Third, the original model states that stage 2 letter representations CUP & 9UD both map onto one stage 3 word-centred grapheme representation <C><U><P>. However, mirror-reversed words are not automatically mapped onto the stage 3 representation of the modified model, which would assume application of a strategy, e.g., the reversed stimulus is read right-to-left and letter-by-letter to produce a left-toright image, which may be subject to neglect.

The orthographic lexicon is thought to occupy non-retinotopic TE, which contributes neurons selectively tuned to whole familiar letter-strings (words and subword units) to the re-entrant dynamic representation. In the manner suggested by Plaut et al. (1996), TE units feed forward to intact phonological lexical processing mechanisms, perhaps in the left posterior superior temporal gyrus (Small et al., 1996). Indeed, the weak lexical influence on deletion rate in Experiment 1 does not necessarily imply additional lexical impairments. Thus, Behrmann et al. (1998) argue that the lexical effects shown by letter-by-letter readers reflect intact top-down lexical influences on degraded prelexical visual processes.

It has already been suggested that double letter deletion partly reflected lateral inhibition between adjacent letter representations. Briefly, competition particularly increased ambiguity at points in the signal where the identity of adjacent letters was the same. This may end in "winner-take-all" deletion of the weakest letter representation and it may explain TR's tendency to insert a gap between doubled letters in Experiment 4. Competition is hypothesised to occur at all levels of the dynamic representation. On the one hand, if letter deletions were due to dysfunction of the V1 cortical feature map, then lateral inhibition between V1 neurons (macaque RF area  $0.5^{\circ}$ ) representing same letters would be stronger when letters are separated by a single character space  $(0.4^{\circ})$  than by a larger space. However, the size of the inter-symbol gap did not alter error rate in Experiments 1, 5, and 6. On the other hand, symbol deletions cannot depend solely on competition between damaged non-retinotopic

TE representations of word and subword units. Also, as only adjacent letters are deleted, the competing representations probably at least coarsely encode retinotopic location. Therefore, it is concluded that deletions at least partly reflect competition between damaged ensembles tuned to abstract letter identities (and perhaps letter-shape representations) in the human homologues of V4/TEO (i.e., in intermediate retinotopic cortex with larger RF sizes).

To explain TR's fragmented percepts, it is argued that whole stimuli resolved without fragmentation if the initial forward progression of the signal activated one TE ensemble. However, anterior extrastriate damage meant that one TE ensemble often failed to achieve supra-threshold activation; that is, damage to word/subword and letter identity representations yielded an ambiguous response to the information in the signal. (Though the parahippocampal damage evident on TR's CT scan is too small to explain her initial severe visual agnosia and permanent prosopagnosia, its anterior location suggests the dysfunction encompassed TE, TEO and perhaps V4 circuits.) It might be argued that ambiguous anterior extrastriate responses corresponded to TR's blurred percepts. She next divided the blurred region into 2 or 3 segments. (Unpublished experiments by the author show that successive fragment resolution still occurred when saccades were excluded by using brief stimulus exposures). As we have seen, the Rolls and Deco (2002) model permits the possibility that covert shifts in spatial attention may be effected via parietal projections to V1 (and perhaps V4/TEO). Essentially, parietal modulation would sequentially facilitate activity in different regions of the persisting (200-300 msec) and dynamically re-cycling representation of the string. This activation would effectively feed forward data in the region of one unresolved segment, and enable compromised anterior extrastriate networks to largely dedicate processing to that segment. Once that signal was resolved, parietal projections would highlight another zone.

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#### References

- BAVELIER D and POTTER MC. Visual and phonological codes in repetition blindness. *Journal Experimental Psychology:* Human Parcention and Parformance, 18:134-147, 1002
- Human Perception and Performance, 18: 134-147, 1992. BEHRMANN M, PLAUT DC and NELSON J. A literature review and new data supporting an interactive account of letter-by-letter reading. Cognitive Neuropsychology, 15: 7-51, 1998.
- BEHRMANN M and SHALLICE T. Pure alexia: A nonspatial visual disorder affecting letter activation. *Cognitive Neuropsychology*, 12: 409-454, 1995.
- CARAMAZZA A and HILLIS AE. Levels of representation, coordinate frames, and unilateral neglect. *Cognitive Neuropsychology*, 7: 391-445, 1990.

- DESIMONE R, SCHEIN SJ, MORAN J and UNGERLIEDER LG. Contour, color and shape analysis beyond the striate cortex. *Vision Research*, 25: 441-452, 1985.
- FARAH MJ. Visual Agnosia: Disorders of Object Recognition and What They Tell Us about Normal Vision. Cambridge, MA: MIT Press, 1990.
- FARAH MJ and WALLACE MA. Pure alexia as a visual impairment: A reconsideration. Cognitive Neuropsychology, 8: 313-334, 1991.
- HALL DA, HUMPHREYS GW and COOPER CG. Neuropsychological evidence for case-specific reading: Multi-letter units in visual word recognition. *Quarterly Journal of Experimental Psychology, 54A*: 439-467, 2001.
- HASSELMO ME, ROLLS ET and BAYLIS GC. The role of expression and identity in the face-selective responses of neurons in the temporal visual cortex of the monkey. *Behavioural Brain Research*, 32: 203-218, 1989.
- HUMPHREYS GW and PRICE CJ. Visual feature discrimination in simultanagnosia: A study of two cases. *Cognitive Neuropsychology*, 11: 393-434, 1994.
- KANWISHER N. Repetition blindness and illusory conjunctions: Errors in binding visual types with visual tokens. Journal Experimental Psychology: Human Perception and Performance, 17: 404-421, 1991.
- LEVINE DN and CALVANIO R. A study of the visual defect in verbal-alexia simultanagnosia. *Brain*, 101: 65-81, 1978.
- MICELI G, BENVEGNU B, CAPASSO R and CARAMAZZA A. Selective deficit in processing double letters. *Cortex*, *31*: 161-171, 1995.
- MAYALL K and HUMPHREYS GW. Presentation and task effects on migration errors in attentional dyslexia. *Neuropsychologia*, *40:* 1506-1515, 2002.
- NELSON HE and WILLISON JR. National Adult Reading Test, Second Edition. Windsor: NFER-NELSON, 1991.
- PLAUT DC, MCCLELLAND JL, SEIDENBERG MS and PATTERSON K. Understanding normal and impaired word reading:

Computational principles in quasi-regular domains. *Psychological Review, 103:* 56-115, 1996.

- RIDDOCH MJ and HUMPHREYS GW. Birmingham Object Recognition Battery. Hove: Lawrence Erlbaum, 1993.
- ROLLS ET and DECO G. Computational Neuroscience of Vision. New York: Oxford University Press, 2002.
- ROLLS ET and TOVEE MJ. Processing speed in the cerebral cortex and the neurophysiology of visual masking. *Proceedings of Royal Society of London, Series B, 257:* 9-15, 1994.
- ROLLS ET, TOVEE MJ and PANZERI S. The neurophysiology of backward visual masking: Information analysis. *Journal of Cognitive Neuroscience*, *11*: 300-311, 1999.
  SAFFRAN EM and COSLETT H. 'Attentional dyslexia' in Alzheimer's
- SAFFRAN EM and COSLETT H. 'Attentional dyslexia' in Alzheimer's disease: A case study. *Cognitive Neuropsychology*, 13: 205-228, 1996.
- SHALLICE T and WARRINGTON EK. The possible role of selective attention in acquired dyslexia. *Neuropsychologia*, 15: 31-41, 1977.
- SMALL SL, NOLL DC, PERFETTI CA, HLUSTIK P, WELLINGTON R and SCHNEIDER W. Localizing the lexicon for reading aloud: Replication of a PET study using fMRI. *Neuroreport*, 7: 961-965, 1996.
- TANAKA K, FUJITA I, KOBATAKE E, CHENG K and ITO M. Serial processing of visual object-features in the posterior and anterior parts of the inferotemporal cortex. In Ono T, Squire LR, Raichle ME, Perret DI and Fukuda M (Eds), Brain Mechanisms of Perception and Memory: From neuron to behaviour. New York: Oxford University Press, 1993.
- YOUNG AW, NEWCOMBE F and ELLIS AW. Different impairments contribute to neglect dyslexia. *Cognitive Neuropsychology*, 8: 177-191, 1991.

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