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Constraints on integration of orthographic information across multiple stimuli: effects of contiguity, eccentricity, and attentional span

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Abstract

Five flanked lexical decision experiments investigated the integration of information across spatially distinct letter strings. Experiment 1 found no significant difference between quadrigram flankers (e.g., CKRO ROCK CKRO) and double bigram flankers (e.g., CK RO ROCK CK RO). Experiment 2 varied the eccentricity of single bigram flankers and found that closer flankers generated greater effects. A combined analysis of these experiments revealed that the double bigram condition (Experiment 1) was less effective than the close single bigram condition (Experiment 2). Experiment 3 tested one explanation for this pattern – that the outer bigrams in the double bigram condition interfered with processing the inner bigrams, and that spatial integration only operates across adjacent stimuli. In Experiment 3, outer bigrams were now a repeat of the inner bigram (e.g., RO RO ROCK CK CK), and this repeated bigram condition was still found to be significantly less effective than single bigrams. Experiments 4 and 5 tested an alternative explanation whereby the addition of spatially distinct flanking stimuli increases the spread of spatial attention, hence reducing the impact of proximal flankers. In line with this explanation, we found no significant difference between repeated bigram flankers and a condition where only the inner bigram was related to the target (e.g., CA RO ROCK CK SH). We conclude that spatial integration processes only operate across the central target and proximal flankers, and that these effects are diluted by the increased spread of spatial attention caused by additional spatially distinct flankers.

Keywords Reading · Flankers task · Orthographic processing · Spatial integration · Spatial attention

Introduction

Following the seminal study of Dare and Shillcock (2013), a new line of research on orthographic processing and reading has emerged (e.g., Cauchi et al., 2020; Snell et al., 2017, 2018). This line of research has adapted the flankers task (Eriksen, 1995) to study the processing of multiple orthographic stimuli. In this reading version of the flanker's task, central target words are flanked to the left and to the right by letter strings (words or nonwords) that are related to the target or not. Testing bigram flankers, Dare and Shillcock found that lexical decisions to target words were facilitated by orthographically related bigrams (e.g., RO ROCK CK vs. BA ROCK TH), and that this flanker facilitation was independent of the location of the bigrams such that 'CK ROCK RO' generated as much facilitation as 'RO ROCK CK'. This pattern was replicated by Grainger et al. (2014), who further reported that letter order within bigrams did matter, such that 'OR ROCK KC' generated less facilitation than 'RO ROCK CK'. Grainger et al. (2014) provided an explanation for these findings in terms of the spatial integration of orthographic information extracted from spatially distinct strings of letters into a single channel for orthographic processing and word identification. The version of the model described in Grainger (2018) is reproduced here to facilitate presentation of the initial hypothesis to be tested in the present work (see Fig. 1). The model is basically an extension of the Grainger and van Heuven (2004) model to the processing of multiple spatially distinct strings of letters. One fundamental

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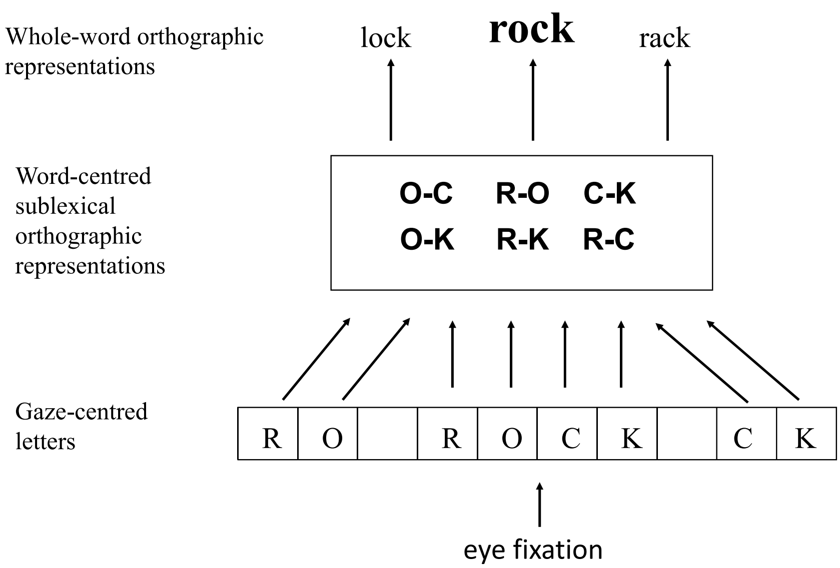

Fig. 1 Spatial integration of orthographic information spanning multiple letter strings (Grainger, 2018; Grainger et al., 2014). Orthographic information provided by flanker and target strings is pooled into a single channel for location invariant orthographic processing. The word-centred sublexical orthographic representations depicted here form a bag of open-bigrams (Grainger & van Heuven, 2004). Hyphenation is used to indicate that the letter combinations are not necessarily contiguous. Not shown in this example are bigrams formed using inter-word space information (i.e., external letters: e.g., #-R, K-#, see Grainger et al., 2014), as well as a possible role for a bag of position-independent letters (Snell et al., 2018). Feedback and lateral connectivity are also not shown

mechanism in the Grainger and van Heuven model is that the order of letters in a letter string, independently of where readers' eyes are looking at that string, is encoded using open-bigrams – that is, an unordered set of ordered, but not necessarily contiguous, letter combinations such as 'RO' and 'RC' in the word 'ROCK'.[1]

The model depicted in Fig. 1 accounts for effects of flanker relatedness by the increased activity of bigrams in the central processing channel that contribute to identification of the target word (greater bigram activity leading to faster word identification) when the same bigrams occur in flanker stimuli. Individual letters shared across target and flankers also contribute to effects of flanker relatedness via the spatial integration of position-independent letter identities (i.e., a 'bag-of-letters' - Snell et al., 2018), as well as a possible role played by 'external letter bigrams' coded as the combination of a space and a letter (e.g., '#-R', Grainger et al., 2014). However, the explanation of the findings of Dare and Shillcock (2013) offered by Grainger et al. (2014) hinges on the key role played by bigrams in the process of spatial integration, and this is the focus of the present study. In the explanation offered by Grainger et al. (2014) it is important to note that although the order of letters within a given bigram is important, the order of bigrams themselves is irrelevant (i.e., a 'bag-of-bigrams'), hence accounting for the effects found in the 'CK ROCK RO' condition. Furthermore, although a possible inhibitory role of incompatible bigrams is not shown in Fig. 1, it is likely that the net effect of flanker relatedness is a combination of facilitation from compatible bigrams and inhibition from incompatible bigrams. We know, for example, that the simple presence of flankers interferes with target processing, and that this interference effect is modulated by flanker relatedness (e.g., Snell & Grainger, 2018). From a purely methodological perspective, and as is the case with priming studies, the only legitimate comparison when evaluating effects of flanker relatedness is therefore between a related flanker condition and a matched unrelated flanker condition.

Within the bigger picture of text reading by skilled readers, we hypothesize that when a given word is fixated, the identification of that word is influenced not only by the information carried by that word itself, but also by information carried by neighboring words. This is hypothesized to occur via the spatial integration of orthographic information illustrated in Fig. 1. However, the precise nature of the information processed by neighboring words is a highly controversial topic that is theoretically relevant with respect to the serial versus parallel processing debate (see, e.g., Snell & Grainger, 2019, and accompanying commentaries). Within this general debate, one key question is: what is the nature of processing performed on word n+1 when readers

[1] We note that other letter position coding schemes such as the overlap model (Gomez et al., 2008) could also be adapted to this general framework for the spatial integration of orthographic information.

are fixating word n, and can the information extracted from word n+1 influence processing of word n? We know from parafoveal preview experiments that orthographic, phonological, morphological and possibly semantic information can be extracted from word n+1 (see Schotter et al., 2012, for a review). What is less clear is the extent to which such parafoveal information can influence on-going processing of word n (so-called 'parafoveal-on-foveal' effects; see Snell & Grainger, 2019, for a review). Here we start from the minimalist assumption that orthographic information extracted from word n+1 influences the on-going processing of word n via the spatial integration of orthographic information across words n and n+1 (and possibly word n-1), as illustrated in Fig. 1. Whether or not higher-level information is also involved in such spatial integration processes is orthogonal to the aims of the present study.

In the present study we focus on testing predictions derived from the model described in Fig. 1 within the specific context of orthographic flanker effects.[2] We return to discuss the more general implications of our findings with respect to everyday text reading in the *General discussion*. In Experiment 1 we compared effects of double bigram flankers (e.g., CK RO ROCK CK RO) with effects of quadrigram flankers (e.g., CKRO ROCK CKRO). Table 1 provides a summary of the conditions tested in Experiment 1. In predicting the pattern of effects to be obtained with these manipulations we made two main assumptions:

1) Orthographic processing can extend to at least four to five character spaces beyond the edges of a four-letter target. Evidence that this is a possibility was provided by Snell et al. (2018), who found significant effects of flanker relatedness with six-letter targets and three-letter flankers, thus suggesting that orthographic information can be extracted in parallel from letters spanning a total of 14 character spaces (see McConkie & Rayner, 1975, and Rayner et al., 2010, for estimates of the span of effective vision obtained with the moving-window paradigm during text reading, and Jordan et al., 2016, for a re-evaluation of the leftward extent of the span).

2) Open-bigrams are only created within a letter string bounded by spaces. This was already assumed in the original Grainger et al. (2014) model in order to prevent activation of bigrams that are incompatible with targets in the related flankers condition, such as 'O-R' in the example in Fig. 1.

Applying the second constraint to the related flanker conditions to be tested in Experiment 1 (see Table 1), combined with the principles of open-bigram coding, it is clear that quadrigram flankers should generate more incompatible bigrams than double bigram flankers. For example, the flanker 'CKRO' will not only generate compatible bigrams 'CK' and 'RO', but also the incompatible bigrams 'CR', 'KR', 'KO'. Therefore, effects of flanker relatedness should be greater for double bigram flankers than quadrigram flankers.

[2] Note that adding a 'bag-of-letters' or 'external letter bigrams' to this model does not affect our predictions.

Table 1 Examples of the different target-flanker sequences tested in Experiment 1 for word and nonword targets

Word	*Related*	Double Bigram	CK RO ROCK CK RO
		Quadrigram	CKRO ROCK CKRO
	Unrelated	Double Bigram	SH CA ROCK SH CA
		Quadrigram	SHCA ROCK SHCA
Nonword	*Related*	Double Bigram	RN KU KURN RN KU
		Quadrigram	RNKU KURN RNKU
	Unrelated	Double Bigram	RK MO KURN RK MO
		Quadrigram	RKMO KURN RKMO

Experiment 1

Methods

Participants

One hundred and twenty native speakers of English (76 women) participated using their personal computer in a 15-min online experiment. The age of participants ranged from 19 to 65 years (M = 36.18 years; SD = 11.41). In this and the following experiments participants received £2 in compensation. The purpose of the experiment was not revealed to participants. Prior to initiation of the experiment, participants were informed that data would be collected anonymously, and they then provided informed consent for participation, as well as information concerning age, native language and gender.

Stimuli and design

We first selected 120 four-letter English target words using the LexOPS package (Taylor & al., 2020) in the R statistical computing environment (R Core Team, 2017). The 120 target words had a SUBTLEX-UK frequency (van Heuven et al., 2014) between 2.3 and 7.7 Zipf (average = 4.39; SD = 0.68), and were nouns, verbs or adjectives (nouns and verbs were uninflected). Target words did not contain adjacent repeated letters. We then generated for each target word an associated four-letter orthographically unrelated control word that was used to generate the unrelated flanker conditions (average orthographic Levenshtein distance = 3.25; SD = 0.72). The control words were matched in frequency to the corresponding target words (average control word frequency = 4.31, SD = 0.64). The target and control word pairs were not semantically related (root cosine semantic similarity <

0.5; Buchanan et al., 2012). Target and control words had the same consonant-vowel structure and the control words did not contain adjacent letter repetitions. Control words could share at most two letters with targets but never shared a bigram formed of the first and second letters or the third and fourth letters. Note that the matching process was done individually for each target. In addition to these 120 word pairs, we also generated 120 four-letter nonwords using the 'Wuggy' pseudoword generator (Keuleers & Brysbaert, 2010). When applicable, we applied the same constraints as for the word targets in generating matched unrelated nonwords to the nonword targets (i.e., they had the same consonant-vowel sequence as targets and did not contain adjacent repeated letters). The nonword targets were included for the purpose of the lexical decision task.

Each target (word or nonword) was presented with flanking letters on the right and the left separated from the target by a single character space (see Fig. 1). The flanking letters were derived either from the target in the related flanker condition or from the matched control word/nonword in the unrelated flanker condition. Flanking letters could either be two bigrams (the 'double bigram' flanker condition) or a single quadrigram. The same flanking letters were presented to the left and to the right of targets. Related flankers were formed of the two last letters of the target followed by the two first letters (e.g., CK RO from the word ROCK in the bigram flanker condition, and CKRO in the quadrigram flanker condition). Unrelated flankers were derived in the same way from the matched control word/nonword. Each target was tested in both the related and unrelated conditions and in both the bigram and quadrigram flanker conditions (see Table 1) leading to a 2 (Relatedness) × 2 (Flanker Type) factorial design. A Latin-square was used such that each of the four types of target-flanker sequence derived from the same target word/nonword were tested with different participants, and each participant was tested in all four conditions across different targets. Thus, four counterbalanced lists were created, and in this and the following experiments participants were randomly and equally assigned to one of the lists. There were 30 trials per condition per participant, and therefore a total of 240 trials per participant.

Apparatus

The experiment was created with Labvanced (Finger et al., 2017) and we used the Prolific platform (Palan & Schitter, 2018) to recruit participants.

Procedure

Seated in front of their computer screen, participants were asked to click on the screen to launch the experiment. After that, they were shown the complete set of instructions for the experiment on a single page. Once they had read and understood the instructions, the participant could start the practice trials by pressing the space bar. The practice session was composed of eight trials that were representative of the eight conditions tested in the main experiment but were not included in the main experiment. Once the practice session was complete, participants were prompted to press the space bar when they were ready to begin the main experiment. Participants were instructed to determine as rapidly and as accurately as possible if the four-letter sequence in the center was a correct English word or not. Each trial started with vertical bars for 500 ms indicating the center of the upcoming sequence (target plus flankers) and participants were instructed to fixate the space between the two vertical bars.[3] Then the sequence was presented for 200 ms followed by a blank screen displayed until the participant's response. As is typical in experiments using the flanker's task, a short stimulus (target + flanker) presentation time was used to minimize the possibility of eye movements away from the central fixation bars and toward the flankers. Participants were instructed to press the right arrow key on their computer keyboard if they thought that the central letter string was a correct English word, or to press the left arrow if not. After their response, they received feedback in the form of a green circle (correct response) or a red cross (incorrect response) shown for 500 ms. A pause was proposed after every 80 trials. The procedure is illustrated in Fig. 2.

Analysis

In this and the following experiments only data pertaining to word targets were analyzed and reported.[4] We used Linear Mixed Effects Models (LMEs) to analyze response times (RTs) and Generalized (logistic) Linear Mixed Effects Models (GLMEs) to analyze error rates, with participants and items as crossed random effects (Baayen et al., 2008; Barr et al., 2013). The models were fitted with the lmer (for

[3] We readily acknowledge that fixation cues and instructions are not a guarantee that participants' gaze was indeed directed at the desired fixation location (Jordan et al., 1998). However, the vast majority of deviant fixations (+/- 0.5° of visual angle) in the Jordan et al. study remained within the boundaries of a four-letter word (1.1° of visual angle) in their study. We are therefore confident that our participants were fixating the target stimulus, as per instructions.

[4] However, following the request of an anonymous reviewer, we nevertheless analyzed the results for nonword targets in exactly the same way as for the word targets. The only interpretable effect to emerge was in Experiment 2, and this is reported in the *Discussion* section of that experiment. Furthermore, since some of the unrelated flankers did share one letter with targets, we checked to see if that impacted on responses in the unrelated conditions in Experiment 1. This was not the case.

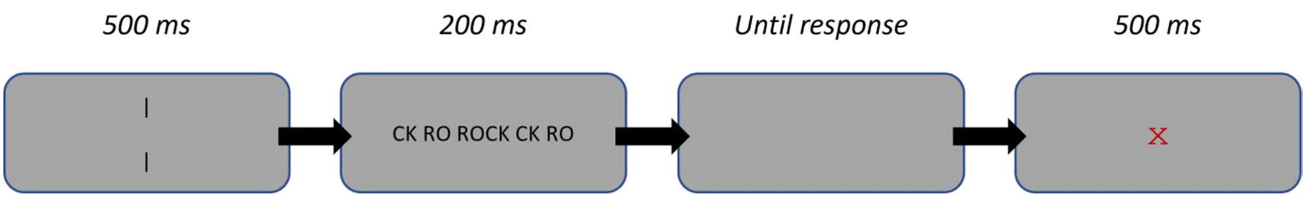

Fig. 2 Procedure of one experimental trial with an example of the related 'double bigram' condition and feedback indicating an incorrect response

LMEs) and the glmer (for GLMEs) functions from the lme4 package (Bates et al., 2015) in the R statistical computing environment (R Core Team, 2017). We report regression coefficients (b), standard errors (SE) and t-values (for LMEs) or z-values (for GLMEs). Fixed effects were deemed reliable if |t| or |z| > 1.96 (Baayen et al., 2008) and significant effects are highlighted in bold font. RTs were log transformed prior to analysis to normalize the distribution. We used the maximal random structure model that converged (Barr et al., 2013), and this included by-participant and by-item random intercepts.

Results

Prior to analysis, one subject was removed because their average RT was too long (> 1,000 ms). All participants performed with accuracy above 75%, but two items were removed due to their average accuracy being lower than 75%. The remaining dataset was composed of 14,042 observations, a number that largely exceeds the recommendation of Brysbaert and Stevens (2018) for having sufficient power. The recommended minimum number of trials per condition was exceeded in all experiments of this study.

Response times

We first excluded trials with incorrect responses (5.43%) and values lying beyond 2.5 standard deviations from each participant mean in each condition (2.43%). The remaining dataset was composed of 12,957 observations. Results are shown in Fig. 3. In this and the following experiments, beta (*b*) and standard error (SE) values obtained in the LME analysis of RTs were multiplied by 1,000 in order to facilitate interpretation.

There was a significant main effect of Relatedness (*b* = 9.17, SE = 1.22, *t* = **7.54)**, with faster RTs in the related condition. The main effect of Flanker Type was not significant (*b* = -0.12, SE = 1.52, *t* = 0.08), and neither was the Relatedness × Flanker Type interaction (*b* = -1.02, SE = 2.43, *t* = 0.42).

Error rates

The dataset for error rates was composed of 14,042 observations. Results are shown in Fig. 4. The main effect of Relatedness was significant (*b* = -0.27, SE = 0.07, *z* = **3.72)**, with fewer errors in the related flanker condition. No significant effect of Flanker Type was found (*b* = 0.13, SE = 0.10, *z* =

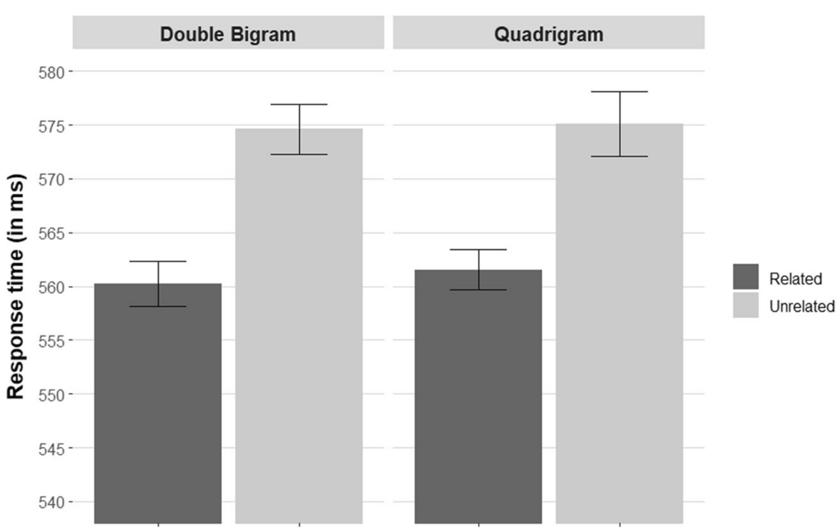

Fig. 3 Mean response times (in ms) for word items according to Flanker Type and Relatedness in Experiment 1. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

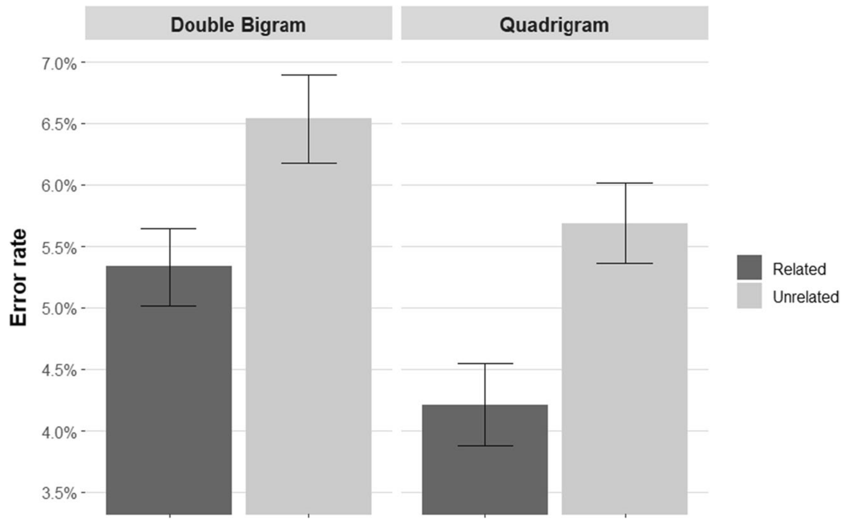

Fig. 4 Mean error rates (in %) for word items according to Flanker Type and Relatedness in Experiment 1. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

1.27). The Relatedness × Flanker Type interaction was not significant (*b* = -0.13, SE = 0.15, *z* = 0.88).

Discussion

The predicted advantage for double bigram flankers compared with quadrigram flankers was not found. Flanker Type did not interact with Relatedness in either RTs or error rates. One possible reason for the failure to find greater effects with double bigram flankers than quadrigram flankers is that on average flanker letters are located at a greater distance from the target in the double bigram condition (see Table 1). Experiment 2 therefore examined whether flanker-target distance impacts on flanker effects with single bigram flankers (see Table 2 for a summary of the conditions).

Experiment 2

Methods

Participants

One hundred and twenty native speakers of English (62 women) participated using their personal computer in a 15-min online experiment. The age of participants ranged from 18 to 64 years (M = 38.90 years; SD = 11.19).

Design and stimuli

We used the same set of target stimuli (word and nonword) as in Experiment 1. For this experiment, each sequence was presented with the target word/nonword in the center flanked on each side by a single bigram (two first letters on the left and two last letters on the right). The distance separating the bigram flanker from the edges of the central target was manipulated. In the ‘close’ condition targets and flankers were separated by one character space. In the ‘distant’ condition targets and flankers were separated by four character spaces (see Table 2). Each word and nonword presentation were tested in both related and unrelated conditions and in both the close and distant conditions leading to a 2 (Relatedness) × 2 (Distance) factorial design. A Latin-square design was used such that each of the four types of sequence derived from the same base word/nonword were tested with different participants, but each participant was tested in all four conditions across different base sequences. Thus, four counterbalanced lists were created, and participants were randomly assigned to one of the lists. There were 30 trials per condition per participant, and therefore a total of 240 trials per participant.

Table 2 Examples of the different target-flanker sequences tested in Experiment 2

Word	*Related*	Close	RO ROCK CK
		Distant	RO ROCK CK
	Unrelated	Close	CA ROCK SH
		Distant	CA ROCK SH
Nonword	*Related*	Close	FR FRIF IF
		Distant	FR FRIF IF
	Unrelated	Close	SP FRIF EN
		Distant	SP FRIF EN

The distance separating the ‘distant’ flankers in Experiment 2 from central targets was the same as the distance for the exterior bigrams in the ‘double bigram’ condition of Experiment 1

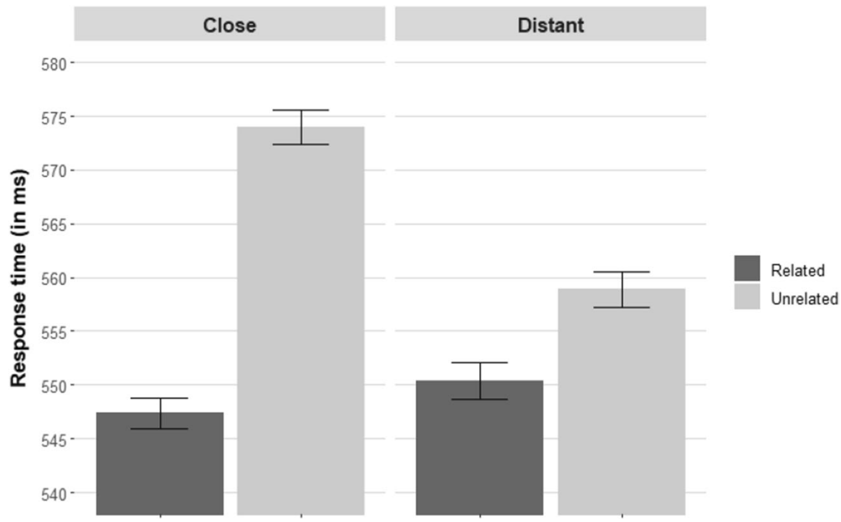

Fig. 5 Mean response times (in ms) for word items according to Distance and Relatedness in Experiment 2. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

Apparatus, procedure and analysis

These were the same as for Experiment 1.

Results

Prior to analysis, one participant was removed due to an excessively long average RT (> 1,000 ms). All participants performed with accuracy above 75%, but three items were removed prior to analysis due to their average accuracy being lower than 75%. The remaining dataset was composed of 13,923 observations.

Response times

We first excluded trials with incorrect responses (5.47%) values lying beyond 2.5 standard deviations from each participant mean in each condition (2.07%). The remaining dataset was composed of 12,888 observations. Results are shown in Fig. 5.

There was a significant effect of Relatedness ($b = 13.39$, SE = 1.17, $t = \mathbf{11.40}$), with faster RTs in the related flanker condition. There was a significant effect of Distance ($b = -4.92$, SE = 1.34, $t = \mathbf{3.66}$), with slower RTs in the close flanker condition. The Relatedness × Distance interaction was also significant ($b = -13.76$, SE = 2.35, $t = \mathbf{5.86}$). Effects of flanker relatedness were greater for close single bigram flankers than distant single bigram flankers.

Error rates

The dataset for error rates was composed of 13,923 observations. Results are shown in Fig. 6. We found a significant effect of Relatedness ($b = -0.23$, SE = 0.09, $z = \mathbf{2.47}$), with fewer errors in the related flanker condition. There was also a significant effect of Distance ($b = 0.32$, SE = 0.08, $z = \mathbf{4.29}$) with more errors in the close single bigram flanker condition. The Relatedness × Distance interaction was not significant ($b = 0.15$, SE = 0.15, $z = 1.03$).

Discussion

Experiment 2 found the predicted effect of flanker distance with single bigram flankers. Bigrams located further from the target had a significantly smaller impact on target processing.[5] This therefore provides a potential explanation for why the double bigram flankers in Experiment 1 were not more effective than the quadrigram flankers, given the greater overall eccentricity of the bigram flankers. However, an informal examination of the size of the double bigram flanker effects in Experiment 1 and the close single bigram flankers of Experiment 2 suggests that this is not the whole story. We therefore performed a combined analysis involving these two conditions tested in Experiments 1 and 2.

Combined analysis of experiments 1 and 2

In this analysis we contrasted the effects of double bigram flankers in Experiment 1 and the close single bigram flanker condition of Experiment 2. Thus, the design (2 × 2) involved a within-participant manipulation of Flanker

[5] In Experiment 2, we found a significant effect of Distance on RTs to nonword targets ($b = 9.27$, SE = 1.37, $t = \mathbf{6.76}$), with faster RTs in the close flanker condition. We suggest that the closer the flankers were to nonword targets, the more they provided evidence that the target was not a word.

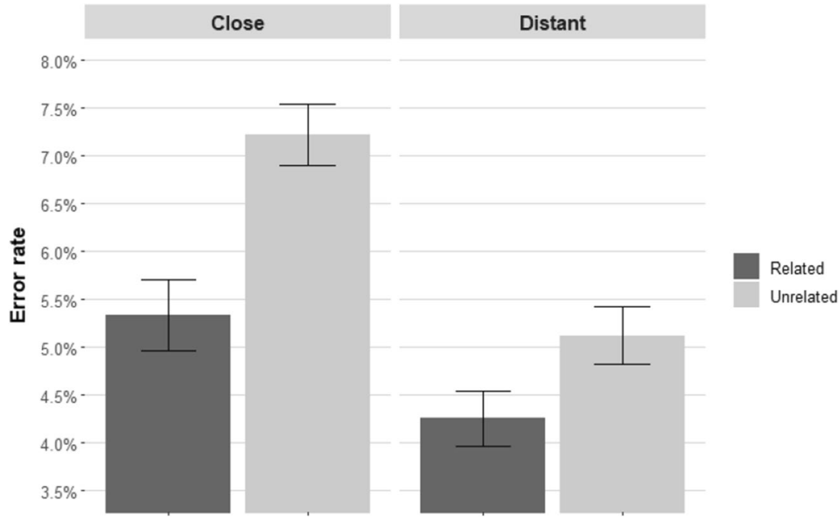

Fig. 6 Mean error rates (in%) for word items according to Distance and Relatedness in Experiment 2. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

Relatedness and a between-participant factor Number of Bigrams. The Number of Bigrams factor therefore did not include by-participant random intercepts.

Results

Response times

The analysis included 6,445 observations for the double bigram condition of Experiment 1 and 6,404 observations for the close single bigram condition of Experiment 2, giving a total dataset of 12,849 observations. Results are shown in Fig. 7.

There was a significant effect of Relatedness (b = 15.09, SE = 1.30, t = **11.61**), with slower RTs in the unrelated condition. The main effect of Number of Bigrams was not significant (b = -5.18, SE = 7.64, t = 0.68), but the Relatedness × Number of Bigrams interaction was (b = 10.42, SE = 2.60, t = **4.01**). The interaction reflects the greater effects of Relatedness in the close single bigram flanker condition of Experiment 2 compared with the double bigram flanker condition of Experiment 1.

Error rates

There were 7,022 observations for the double bigram trials of Experiment 1 and 6,961 observations for the close single bigram trials of Experiment 2, thus giving a total of

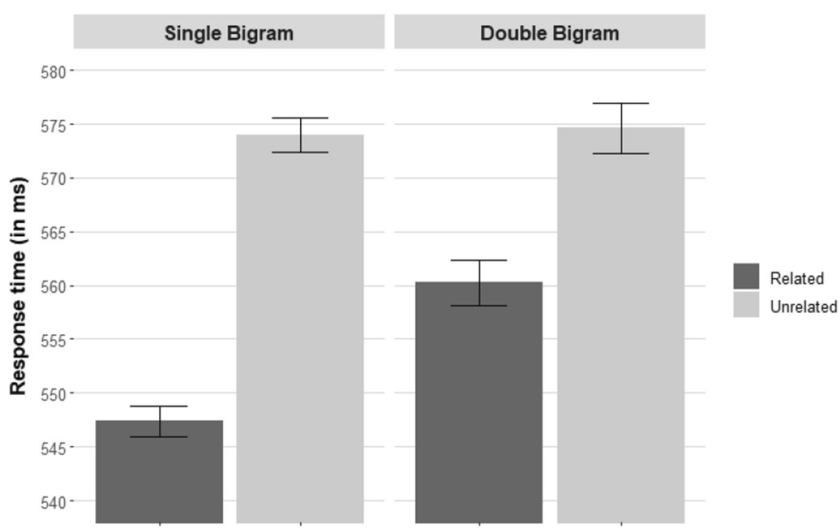

Fig. 7 Mean response times (in ms) for word targets in the close single bigram condition of Experiment 2 and the double bigram condition of Experiment 1 as a function of flanker relatedness. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

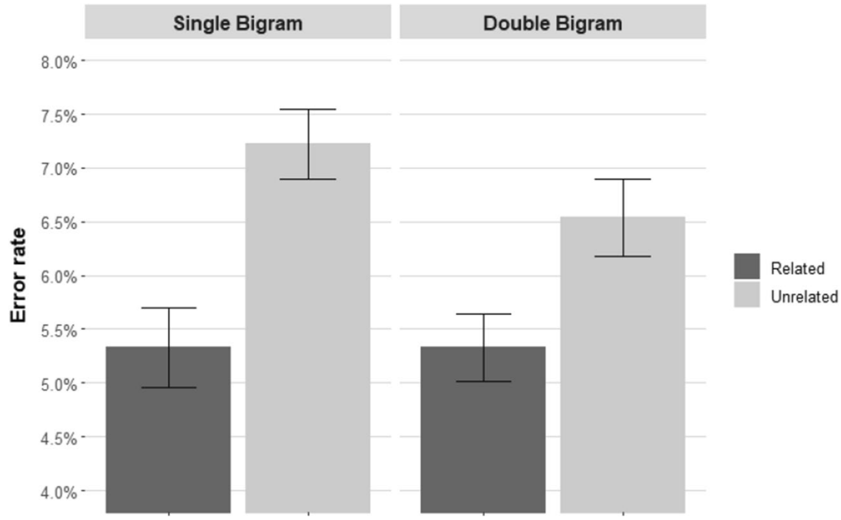

Fig. 8 Mean error rates (in %) for word targets in the close single bigram condition of Experiment 2 and the double bigram condition of Experiment 1 as a function of flanker relatedness. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

13,983 observations for the analysis of error rates. Results are shown in Fig. 8.

There was a main effect of Relatedness (b = -0.28, SE = 0.07, z = **3.97**), with fewer errors in the related condition. The main effect of Number of Bigrams was not significant (b = -0.11, SE = 0.13, z = 0.84), and neither was the Relatedness × Number of Bigrams interaction (b = -0.14, SE = 0.14, z = 0.96).

Discussion

The combined analysis of the double bigram flanker condition of Experiment 1 and the single bigram flanker condition of Experiment 2 revealed a pattern that requires explanation. Single bigrams generated significantly greater effects than double bigrams even although the inner bigrams of the double bigram condition were identical to the single bigram condition (see Tables 1 and 2). Our tentative explanation for this pattern is that the spatial integration of orthographic information only operates across adjacent letter strings, and therefore across target and flankers that are adjacent to targets, and also across adjacent flankers when there is more than one spatially distinct flanker stimulus. So, for example, with the stimulus CK RO ROCK CK RO, the inner bigrams influence processing of the central target word, and the outer bigrams influence processing of the inner bigrams leading to a diminished impact of the inner bigrams given their incompatibility with the outer bigrams (e.g., CK is incompatible with RO). Experiment 3 was designed to test this explanation by changing the nature of the double bigram condition with outer bigrams being identical to inner bigrams (i.e.., repeated bigrams – see Table 3). We expected the repeated bigram condition to generate at least as large effects as the single bigram condition, and possibly stronger effects.

Experiment 3

Methods

Participants

One hundred and twenty native speakers of English (64 women) participated using their personal computer in a 15-min online experiment. The age of participants ranged from 19 to 65 years (M = 37.15 years; SD = 11.52).

Design and stimuli

We used the same target stimuli as in the previous experiments and manipulated flanker relatedness and the nature of the flankers. The Flanker Type manipulation involved a ‘single bigram’ condition that was identical to the ‘close’ condition in Experiment 2, and a ‘repeated bigram’ condition that was the same as the ‘single bigram’ condition except that the same bigram was presented twice separated

Table 3 Examples of the different target-flanker sequences tested in Experiment 3

Word	*Related*	Single Bigram	RO ROCK CK
		Repeated Bigram	RO RO ROCK CK CK
	Unrelated	Single Bigram	CA ROCK SH
		Repeated Bigram	CA CA ROCK SH SH
Nonword	*Related*	Single Bigram	MI MIRK RK
		Repeated Bigram	MI MI MIRK RK RK
	Unrelated	Single Bigram	JA MIRK NC
		Repeated Bigram	JA JA MIRK NC NC

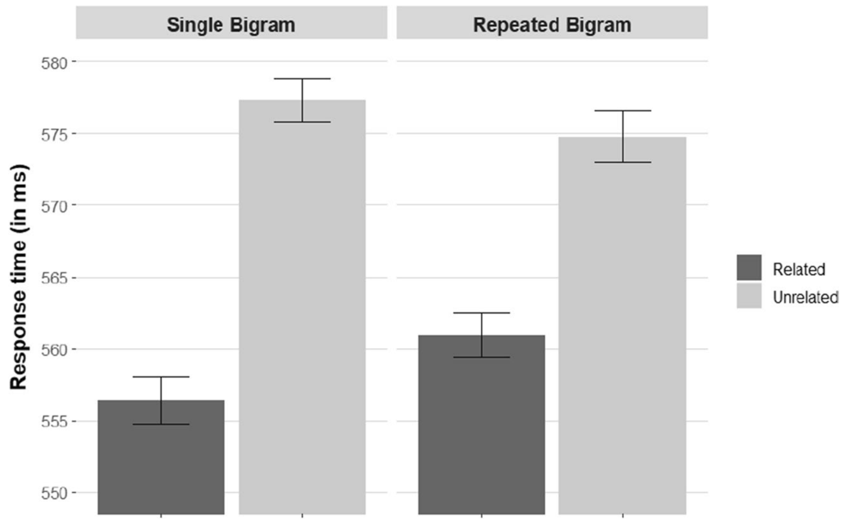

Fig. 9 Mean response times (in ms) for word items according to Flanker Type and Relatedness in Experiment 3. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

by a space (see Table 3). The design was therefore a 2 (Relatedness) × 2 (Flanker Type) factorial. A Latin-square was used such that participants were tested in each of the four experimental condition but saw a given target (word / nonword) only once. Thus, four counterbalanced lists were created, and participants were randomly assigned to one of the lists. There were 30 trials per condition per participant, and therefore a total of 240 trials per participant.

Apparatus, procedure and analysis

These were the same as in the previous experiments.

Results

Prior to analysis, two subjects were removed because their average RT was too long (> 1,000 ms). All participants performed with accuracy above 75%. Prior to analysis, three items were removed due to their average accuracy being lower than 75%. The remaining dataset was composed of 13,806 observations.

Response times

We first excluded trials with incorrect responses (5.47%) and values lying beyond 2.5 standard deviations from each participant mean in each condition (2.24%). The remaining dataset was composed of 12,759 observations. Results are shown in Fig. 8.

There was a significant effect of Relatedness (b = 13.12, SE = 1.51, t = **8.72**), with slower RTs in the unrelated condition. The effect of Flanker Type was not significant (b = -0.00, SE = 1.15, t < 0.01). However, the Relatedness × Flanker Type interaction was significant (b = 5.84, SE = 2.30, t = **2.54**), with greater effects of Relatedness in the single bigram condition Fig. 9.

Error rates

The dataset for error rates was composed of 13,806 observations. Results are shown in Fig. 10. There was a main effect of Relatedness (b = -0.36, SE = 0.10, z = **3.78**), with fewer errors in the related condition. Neither the effect of Flanker Type (b = 0.15, SE = 0.09, z = 1.68) nor the interaction between Flanker Type and Relatedness were significant (b = 0.10, SE = 0.15, z = 0.64).

Discussion

The results of Experiment 3 revealed that single bigram flankers were still more effective than double bigram flankers (greater effects of Relatedness in RTs) even when the double bigrams were formed by repeating the same bigram (i.e., the repeated bigram condition of Experiment 3). We expected repeated related bigrams (e.g., RO RO ROCK CK CK) to at least provide as much facilitation as single related bigrams given the compatibility of the two bigrams located on each side of the target. As a further test of the lack of impact of repeated bigrams, we performed a combined analysis of Experiments 1 and 3 in order to directly contrast the effects of the two types of bigram condition (the double bigram condition of Experiment 1 and repeated bigram condition of Experiment 3).

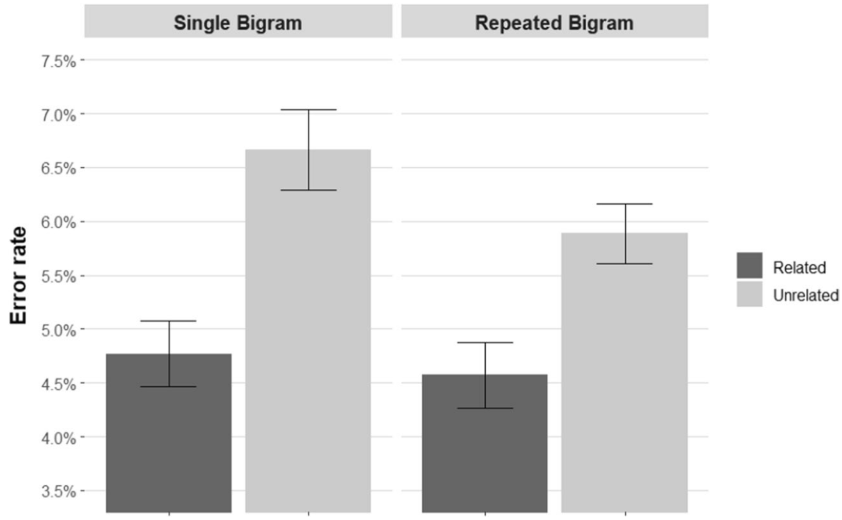

Fig. 10 Mean error rates (in%) for word targets according to Flanker Type and Relatedness in Experiment 3. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

Combined analysis of experiments 1 and 3

We also conducted an analysis based on the data of the double bigram condition tested in Experiment 1 and the repeated bigram condition of Experiment 3 (see Tables 1 and 3). Here we aimed to test whether the repeated bigrams in Experiment 3 generated greater flanker effects than the double bigram condition of Experiment 1. The design was therefore a 2 × 2 factorial involving the within-participant manipulation of Flanker Relatedness and the between-participant factor Bigram Type. The Bigram Type factor therefore did not include by-participant random intercepts.

Results

Response times

There were 6,445 observations for the double bigram condition of Experiment 1 and 6,392 observations for the repeated bigram condition of Experiment 2, thus generating a total dataset of 12,837 observations. Results are shown in Fig. 11.

There was a main effect of Relatedness (b = 10.04, SE = 1.45, t = **6.94**), with faster RTs in the related condition. Neither the main effect of Bigram Type (b = -0.20, SE = 7.77, t = 0.03) nor the Bigram Type × Relatedness interaction were significant (b = 0.24, SE = 2.89, z = 0.08).

Error rates

There were 7,022 observations for the double bigram condition and 6,906 observations for the repeated bigram condition, thus providing a total of 13,928 observations. Results are shown in Fig. 12. There was a significant effect of Relatedness (b = -0.25, SE = 0.07, z = **3.39**), with fewer errors made in the related condition. The main effect of Bigram Type was not significant (b = 0.12, SE = 0.14, z = 0.88), and neither was the Relatedness × Bigram Type interaction (b = -0.07, SE = 0.15, z = 0.44).

Discussion

A comparison of the double bigram condition tested in Experiment 1 (different bigrams) and the repeated bigram condition of Experiment 3 (see Figs. 11 and 12) revealed no significant differences. On the basis of these results we re-affirm that spatial integration only operates across adjacent stimuli, hence target processing is only affected by proximal flankers. However, we now further conclude that the interfering effect of adding bigram flankers is not due to the integration of information across the two spatially distinct flankers on each side of targets, but due to an increase in the spread of spatial attention when more flankers are added. That is, only flankers that are adjacent to targets impact on target processing via spatial integration processes, whereas non-adjacent flankers impact on target processing via a modification of the extent of spatial attention. Experiment 4 tests this interpretation by comparing a condition with repeated bigram flankers (e.g., RO RO ROCK CK CK), as in Experiment 3, with a double bigram condition where only the inner bigrams are related to targets in the related flanker condition (e.g., CA RO ROCK CK SH). We refer to the latter condition as the 'inner bigram' condition. If non-adjacent flankers modulate processing of target words via a change in the spread of attention, then

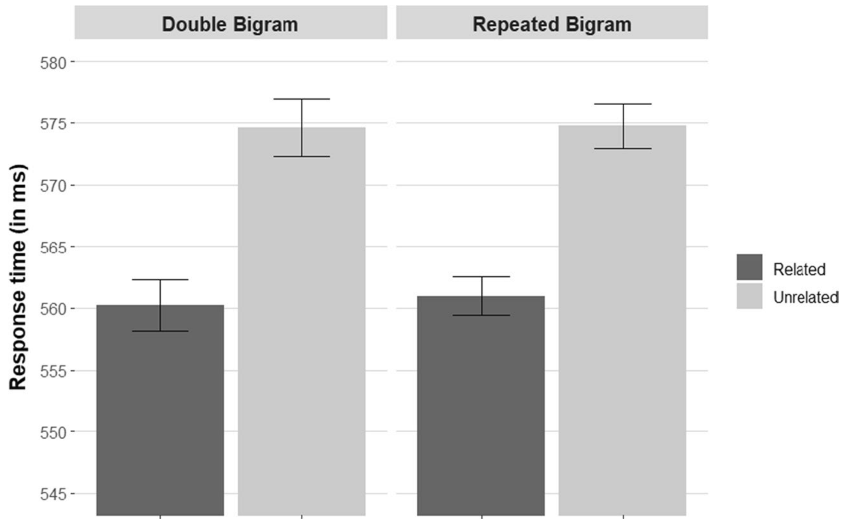

Fig. 11 Mean response times (in ms) for word targets in the Double Bigram condition of Experiment 1 and in the Repeated Bigram condition of Experiment 3 as a function of flanker relatedness. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

there should be no difference between these two conditions, which should both produce facilitation relative to unrelated flankers (e.g., CA LE ROCK ND SH).

Experiment 4

Methods

Participants

Ninety native speakers of English (36 women) participated using their personal computer in a 15-min online experiment. The age of participants ranged from 20 to 64 years (M = 37.82 years; SD = 11.54).

Design and stimuli

We used the same target words and nonwords as in the previous experiments and the same repeated bigram flankers as in Experiment 3. Two new double bigram flanker conditions were tested in Experiment 4: A related inner flanker condition, where only the inner bigrams (one to the left and one to the right) were related to the target (referred to as the 'inner bigram' condition), and a double unrelated bigram condition composed of two different bigrams (two on the left and the

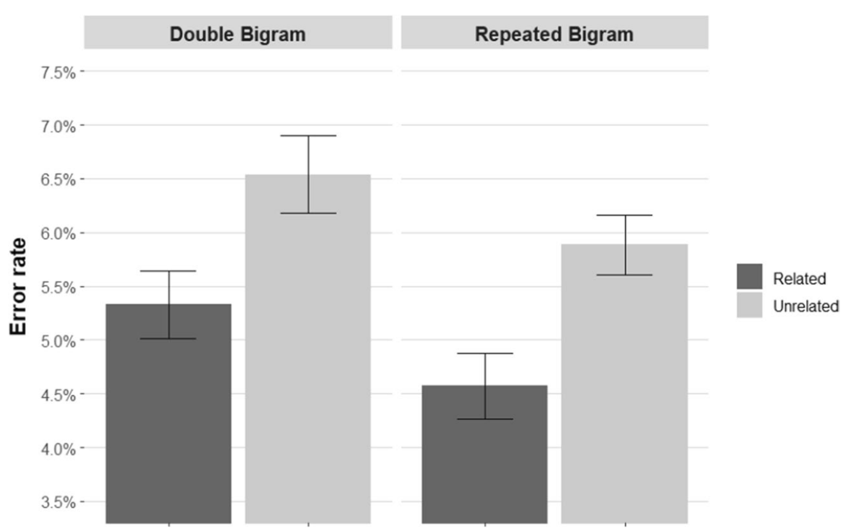

Fig. 12 Mean error rates (in%) for word targets in the double bigram condition of Experiment 1 and in the repeated bigram condition of Experiment 3 as a function of flanker relatedness. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

Table 4 Examples of the different target-flanker sequences tested in Experiment 4

Word	*Related*	Repeated Bigram	`RO RO ROCK CK CK`
		Inner Bigram	`CA RO ROCK CK SH`
	Unrelated		`CA LE ROCK ND SH`
Nonword	*Related*	Repeated Bigram	`MI MI MIRK RK RK`
		Inner Bigram	`JA MI MIRK RK NC`
	Unrelated		`SA LE MIRK SD FP`

same two bigrams on the right), both of which were unrelated to targets. The unrelated bigram flankers were matched in structure with the inner bigram flankers by replacing the inner bigrams with unrelated bigrams derived from a different word/nonword (see Table 4 for examples). The Flanker Type manipulation therefore involved a 'repeated bigram' condition, an 'inner bigram' condition, and an 'unrelated' condition for both word and nonword targets. A Latin-square was used such that participants were tested in each of the three experimental conditions, but saw a given target (word/nonword) only once. Thus, three counterbalanced lists were created, and participants were randomly assigned to one of the lists. There were 40 trials per condition per participant, and therefore a total of 240 trials per participant. Data were analyzed using three contrasts: 'repeated bigram' versus 'inner bigram'; 'repeated bigram' versus 'unrelated'; 'inner bigram' versus 'unrelated'.

Results

All participants had average RTs of less than 1,000 ms. Two participants and four items were removed due to their average accuracy being lower to 75%. The remaining dataset was composed of 10,208 observations.

Response times

We first excluded trials with incorrect responses (5.08%) and values lying beyond 2.5 standard deviations from each participant mean in each condition (2.53%). The remaining dataset was composed of 9,444 observations. Results are shown in Fig. 13.

The difference between the repeated bigram and inner bigram conditions was not significant ($b = 2.29$, SE = 1.57, $t = 1.46$). On the other hand, the two related conditions generated faster RTs than the unrelated condition: repeated bigram ($b = -12.77$, SE = 1.57, $t =$ **8.11**); inner bigram ($b = -10.48$, SE = 1.58, $t =$ **6.64**).

Error rates

The dataset for error rates was composed of 10,208 observations. Results are shown in Fig. 14.

The difference between the repeated bigram and inner bigram conditions was not significant ($b = -0.07$, SE = 0.11, $z = 0.68$). Neither was the difference between the repeated bigram and unrelated conditions ($b = 0.16$, SE = 0.11, $z = 1.50$), nor the difference between the inner bigram and unrelated conditions ($b = 0.09$, SE = 0.11, $z = 0.82$).

Discussion

Experiment 4 replicated the effects of repeated bigrams found in Experiment 3 with quite similar effect sizes in RTs and error rates relative to the unrelated flanker condition. Crucially, with respect to our proposed interpretation of the advantage for single compared with repeated bigrams found in Experiment 3, there was no significant difference between the repeated bigram and the inner bigram conditions

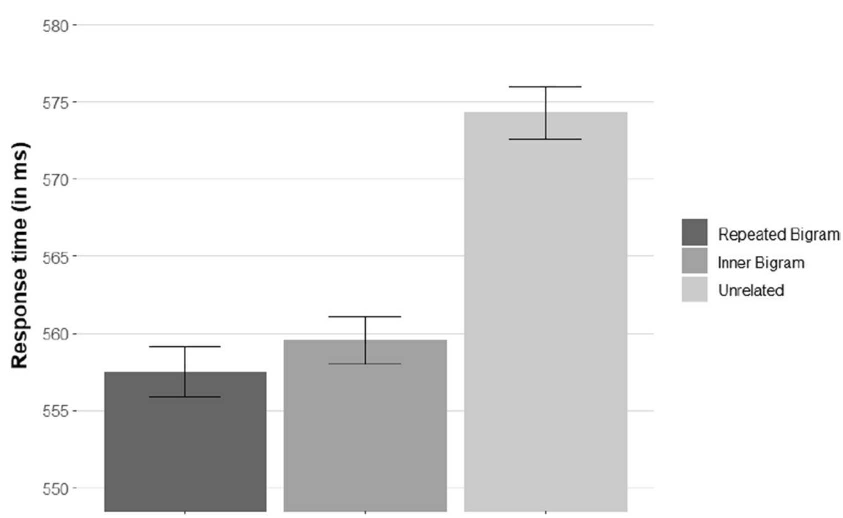

Fig. 13 Mean response times (in ms) for word targets in the three Flanker Type conditions of Experiment 4. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

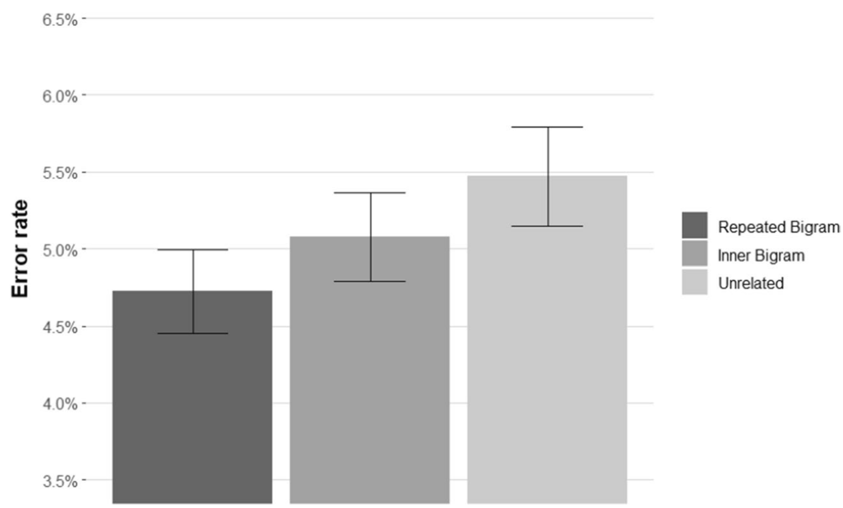

Fig. 14 Mean error rates (in%) for word targets in the three Flanker Type conditions of Experiment 4. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

in Experiment 4. We therefore conclude that outer bigrams (i.e., flankers that are not adjacent to targets) do not contribute to the effects of spatial integration of orthographic information in the flanker's task. Experiment 5 provides a replication of the results of Experiment 4, but this time with a 100-ms stimulus duration. This shorter stimulus duration was chosen in order to provide stricter constraints on the possibility of eye movements to the flanker stimuli (see Bourne, 2006).

Experiment 5

Methods

Participants

Ninety native speakers of English (34 women) participated using their personal computer in a 15-min online experiment. The age of participants ranged from 19 to 65 years (M = 36.64 years; SD = 11.69).

Apparatus, procedure and analysis

These were the same as in the previous experiments except for the change in stimulus duration, which was now 100 ms (instead of 200 ms).

Results

All participants had an average RT lower than 1,000 ms. Two participants and four items were removed due to their average accuracy being lower to 75%. The remaining dataset was composed of 10,208 observations.

Response times

We first excluded trials with incorrect responses (4.57%) and values lying beyond 2.5 standard deviations from each participant mean in each condition (2.40%). The remaining dataset was composed of 9,507 observations. Results are shown in Fig. 15.

The results of the RT analysis mimicked those of Experiment 4 with no significant difference between the repeated bigram and inner bigram conditions (b = 2.81, SE = 1.58, t = 1.78), and significant differences between the two related conditions and the unrelated condition: repeated bigram (b = -9.71, SE = 1.58, t = **6.13**); inner bigram (b = -6.90, SE = 1.58, t = **4.36**).

Error rates

The dataset for error rates was composed of 10,208 observations. Results are shown in Fig. 16.

The difference between the repeated bigram and inner bigram conditions was not significant (b = 0.02, SE = 0.12, z = 0.19). Neither was the difference between the repeated bigram and unrelated conditions (b = 0.14, SE = 0.11, z = 1.26), nor the difference between the inner bigram and unrelated conditions (b = 0.16, SE = 0.11, z = 1.44).

Discussion

The results of Experiment 5 provide a direct replication of the key pattern seen in the RTs of Experiment 4, that there is no significant difference between the repeated bigram and inner bigram flanker conditions. Crucially, the shorter stimulus duration (100 ms) used in Experiment 5 provides support for our hypothesis that the effects of flanker relatedness are

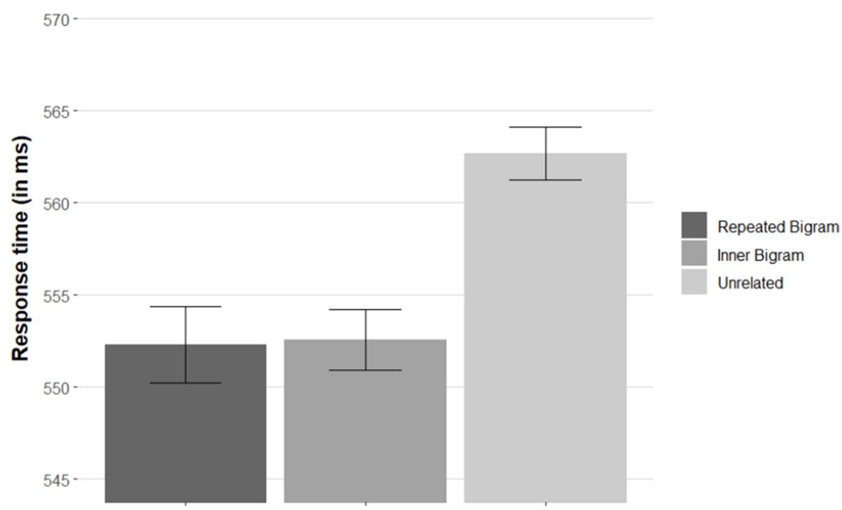

Fig. 15 Mean response times (in ms) for word targets in the three Flanker Type conditions of Experiment 5. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

driven by spatial integration processes that do not require an eye movement to flanker stimuli, and the pattern seen with the repeated bigram and inner bigram flanker conditions provides further support for our hypothesis that such spatial integration processes only operate across the target and adjacent flanker stimuli.

General discussion

In five flanked lexical decision experiments we manipulated the length, the number and the eccentricity of flanker stimuli, as well as their orthographic overlap with targets. Prior research has shown that bigram flankers (e.g., RO ROCK CK) impact on central target processing (ROCK) and do so independently of the location of the flankers (CK ROCK RO), as long as within-bigram letter order respects letter order in the target (Dare & Shillcock, 2013; Grainger et al., 2014). An explanation for this intriguing pattern of effects was provided by Grainger et al. (2014) in terms of the spatial pooling of orthographic information across flankers and target into a single channel for orthographic processing and word identification (see Fig. 1). The first level of processing in this central channel is thought to involve a location-invariant sublexical orthographic code, such as the open-bigram units postulated in the Grainger and van Heuven (2004) model (see also Whitney,

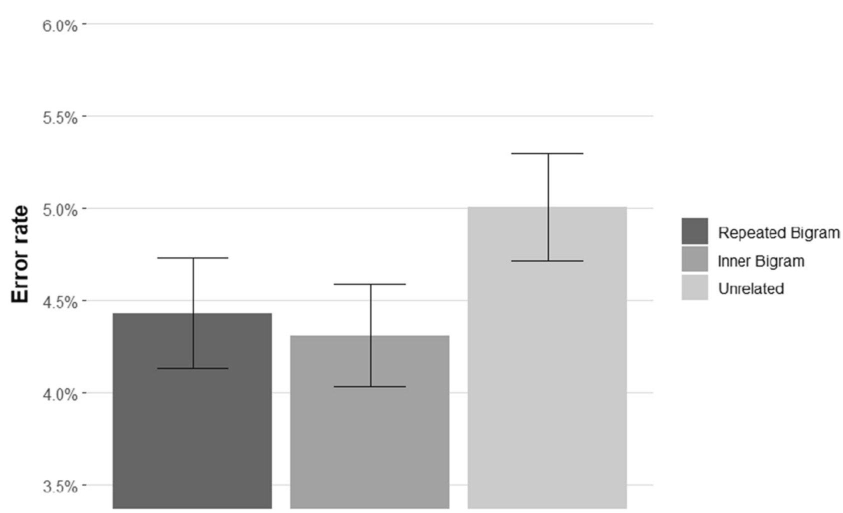

Fig. 16 Mean error rates (in%) for word targets in the three Flanker Type conditions of Experiment 5. Error bars represent within-participant 95% confidence intervals (Cousineau, 2005)

2001). The combination of spatial pooling and open-bigram coding led us to predict that bigram flankers (e.g., CK ROCK RO) should be more effective than quadrigram flankers (e.g., CKRO ROCK CKRO) in facilitating target word identification. This was hypothesized because the quadrigram flankers should generate more open-bigrams that are incompatible with the target (e.g., CR, CO, KR, KO). In order to equate the bigram and quadrigram conditions in terms of orthographic overlap with targets, in Experiment 1 we used double bigram flankers (e.g., CK RO ROCK CK RO). The results of this experiment showed that, contrary to our prediction, double bigram flankers were not more effective than quadrigram flankers.

Experiment 2 tested the possibility that the overall greater eccentricity of flanker stimuli in the double bigram condition of Experiment 1 might have reduced the impact of flanker relatedness in this condition. To do so, we manipulated the eccentricity of single bigram flankers (one-character space vs. two-character spaces from targets) and indeed found that flanker eccentricity had an impact on the effect of flanker relatedness. However, a comparison of the double bigram condition of Experiment 1 (e.g., CK RO ROCK CK RO) with the single close bigram condition of Experiment 2 (e.g., RO ROCK CK) revealed greater flanker facilitation in the single bigram condition. We tentatively hypothesized that the additional bigram flankers in the double bigram condition were interfering in the processing of the proximal flankers and reducing their impact on target processing. In doing so we also hypothesized that the spatial integration (or pooling) of orthographic information only operates across adjacent stimuli. The outer flankers in the double bigram condition would therefore interfere in the processing of the inner bigram flankers and thereby reduce the impact of these flankers on target processing.

Experiment 3 tested this explanation of the pattern of flanker effects found in Experiments 1 and 2. We reasoned that repeating bigrams in the double bigram flanker condition (e.g., RO RO ROCK CK CK) should facilitate target processing more than the single bigram condition (RO ROCK CK) given that the outer bigrams are completely compatible with the inner bigrams in this condition. So, under the assumption that spatial integration only occurs across adjacent stimuli, the outer bigrams should facilitate processing of the inner bigrams and increase the impact of the inner bigrams on target processing. This turned out not to be the case. In Experiment 3 single bigram flankers were still more effective than the repeated bigram flankers.

In an attempt to provide a comprehensive account of the results of Experiments 1–3 we concluded that: (i) spatial integration of orthographic information only operates across the target and adjacent flanking stimuli (i.e., the target and proximal flankers), and (ii) that the number of spatially distinct flankers determines the spread of spatial attention. It is therefore this increase in the spread of spatial attention that is hypothesized to cause the drop in effects of flanker relatedness with double bigram flankers, and this occurs independently of the relatedness of the flankers between themselves (i.e., same or different bigrams). This interpretation was put to test in Experiment 4 (200-ms stimulus duration) and Experiment 5 (100-ms stimulus duration). We predicted no difference between a condition with repeated bigram flankers (as tested in Experiment 3) and a condition where only the inner bigrams were related to targets (the 'inner bigram' condition). We found such a pattern in both experiments. However, both related conditions did generate significantly faster RTs than the unrelated flanker condition. The fact that these flanker relatedness effects were found in Experiment 5 with a 100-ms stimulus duration provides support for our hypothesis that the effects are driven by spatial integration processes that do not require an eye-movement to flanker stimuli.

The present findings place constraints concerning the spatial extent of orthographic processing in the reading version of the flanker's task (Dare & Shillcock, 2013). Given the overarching goal to understand basic processes in reading, it is important to relate our findings to those obtained with different reading paradigms, and notably studies measuring the extent of the perceptual span during text reading. As mentioned in the *Introduction*, studies using the moving-window paradigm suggest that orthographic information can be extracted in parallel across a total of 14 character spaces spanning the location of eye fixation during text reading (e.g., Jordan et al., 2016; McConkie & Rayner, 1975; Rayner et al., 2010). Some studies, however, suggest that the estimated extent of the perceptual span might be less. The results of Underwood and Zola (1986), for example, point to a span of two letters to the left and six or seven letters to the right of fixation. With central fixation on four-letter targets in the present study, the edges of flankers in the 'distant' single bigram condition of Experiment 2 would be at about five to seven character spaces from fixation. So, under the assumption that the rightward bias might be reduced in the flanker's task compared with text reading, the estimate of Underwood and Zola corresponds well with the limits of the spatial extent of flanker effects found in the present study. This leads us to predict that even greater spacing between target and flankers than was implemented in the 'distant' single bigram condition of current Experiment 2 should eventually cancel flanker effects.

What do the present findings tell us about how skilled readers read? The reading version of the flanker's task, first developed by Dare and Shillcock (2013), is clearly a highly simplified window on the processes involved in everyday text reading. Nevertheless, we believe that this paradigm offers important insights into the very first stages involved in processing orthographic information during sentence reading (Grainger, 2018; Snell, van Leipsig, et al., 2018). Our results suggest that only proximal stimuli influence on-going processing of the target. In other words, although there is some evidence for parafoveal preview effects for non-proximal information (i.e., word n+2: see Vasilev & Angele, 2017, for a review), this should not be the case for orthographic parafoveal-on-foveal effects that have been so far observed for word n+1 (Angele et al., 2013; Dare & Shillcock, 2013; Snell et al., 2017). That is, although orthographic information (and possibly other types of information) concerning word n+2 might well be processed during fixation of word n (and therefore generate a parafoveal preview effect when word n+2 is subsequently fixated), information extracted from word n+2 should not affect on-going processing of word n.

In sum, the main conclusions of the present study are threefold. First, spatial pooling of orthographic information only occurs across the fixated stimulus (the target) and proximal (i.e., adjacent) flankers. Second, increasing the distance between the edges of the target and the proximal flanker reduces effects of flanker relatedness. Third, adding more spatially distinct flankers causes an increase in the spread of spatial attention thus diluting the impact of the proximal flankers on target processing. Future research could investigate other factors that impact on the allocation of spatial attention when processing multiple letter strings, over and above the spread of effective vision (the present study) and biases in the direction of reading (e.g., Snell & Grainger, 2018).

Authors' contributions CF: stimulus selection, programming, data analysis, writing; CC: data analysis; MP: data analysis and writing; JG: design and writing.

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Data availability Data and materials are available via the Open Science Framework at: https://osf.io/bj7v5/?view_only=aed81c60322c49d99decc802833c3036

Declarations

Competing interests The authors declare no conflicts of interest.

Ethics approval Ethics approval was obtained from the Comité de Protection des Personnes SUD-EST IV (No. 17/051).

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