

The distractor frequency effect in the colour-naming Stroop task: An overt naming event-related potential study

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We used the event-related potential (ERP) approach to track the time course of the distractor frequency effect in the colour-naming Stroop task, i.e. the longer naming latency when to-be-ignored words are low-frequency rather than high-frequency words. ERPs elicited by coloured words were influenced by distractor frequency in 160–220 ms and 300–400 ms time windows. In a Stroop variant of the colour-naming task, ERPs elicited by coloured words were affected by colour/word congruency in 300–400 ms and 500–600 ms time windows. Temporal and polarity features of distractor frequency and Stroop ERP responses suggest that the distractor frequency effect in the colour-naming Stroop task is characterised by at least two temporally and functionally distinguishable ERP effects: one early effect that we interpret as reflecting the processing of the distractor words and one mid-latency effect reflecting suppression of the distractor word.

Keywords: Distractor processing; Event-related potential; Lexical access; Speech production; Stroop effect; Visual word recognition; Word frequency.

Humans have the capacity to exert cognitive control over their thoughts and actions, to direct and focus their attention towards task-relevant information and to inhibit inappropriate actions or stimuli. The Stroop effect is a paradigmatic test that has been widely used to investigate cognitive control (Stroop, 1935; for a revision see MacLeod, 1991). The colour-naming Stroop task involves processing of coloured word stimuli (e.g., “GREEN” written in red or in green ink) while selectively attending to the ink-colour (the correct response would be “red” or “green”, respectively).

In incongruent trials, the ink-colour and the meaning of the word name do not match, and cognitive control must enable preferential processing in a weaker task pathway (colour naming) over a competing and stronger, but task-irrelevant, pathway (word-reading). As a consequence, reaction times for incongruent trials are slower compared to congruent trials. Interestingly, specific properties of the distractor words can modulate the reaction times as well, suggesting that distractor words gain access and affect one or more stages of processing required for colour name production. In the

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present study, we explore the role of cognitive control in dealing with the interference caused by a lexical property of the task-irrelevant words, word-written frequency.

To date, studies about word frequency effects on the colour-naming Stroop task have shown relatively inconsistent results. In his influential paper, Klein (1964) reported longer reaction times with high-frequency words in relation to low-frequency words (see also Fox, Shor, & Steinman, 1971). This pattern was explained in terms of a horse-race model according to which the word and the colour aspects of the stimulus are processed in parallel until reaching a response buffer. Critically, the response buffer is capacity-limited and can accommodate only one of the two responses. In those trials in which the inappropriate response (i.e., the word) becomes available before the appropriate one (i.e., the ink-colour word), the inappropriate response has to be cleared from the buffer, incrementing reaction times (e.g., Warren, 1972 1974; for a revision, see MacLeod, 1991). The model can account for Klein's observation as high-frequency words would reach the response buffer faster than low-frequency words; therefore, there is a greater chance for an inappropriate response to be generated with high-frequency words. However, the studies by Klein (1964) and Fox and colleagues (1971) have been criticised for methodological reasons, for instance, because of the limited number of words used in each frequency condition and because most of the low-frequency words were very uncommon, and likely some of them were unknown to participants.

Indeed, recent studies have reported mixed results. For instance, in two colour-naming Stroop experiments, Geng, Schnur, and Janssen (2014) did not find a distractor frequency effect. However, previous evidence showed in diverse studies faster colour-naming latencies with high-frequency words than with low-frequency words, in contrast to what originally reported by Klein (Burt, 1994, 1999, 2002; see also Dewhurst & Barry, 2006; and Monsell, Taylor, & Murphy, 2001, although in this last study, the results did not reach the standard value of statistical significance). Burt proposed two assumptions to explain this pattern of results. The first is that in most colour-naming trials, participants read the distractor word (as is generally accepted in the literature of the Stroop task, e.g., MacLeod, 1991). The second is that the faster processing for high-frequency words in comparison with low-frequency word produces "a reduction in the concurrent processing load, or the

duration of the processing overlap" (Burt, 2002, p. 1034), yielding less interference. In line with this account, it has been shown that identity primes reduce the interference of distractor words. That is, when the distractor word is presented as a prime stimulus before its presentation as a target stimulus, there is less interference compared to when a different word is presented as a prime stimulus (Burt, 2002). In accordance with Burt's hypothesis, facilitating base-word processing through an identity prime would reduce the magnitude of the concurrent processing demands, and this would speed up colour-naming latencies.

An alternative account of the task implementation is in terms of competition at the level of task sets (Monsell et al., 2001). As reading is a more practised task, the presentation of a word evokes the associated task of reading. Thus, participants have to suppress the task set of reading before enabling the relevant task set (i.e., colour naming). This first suppression would act as a filter or as a gate, impeding the very trained task, that is reading. However, this filter mechanism is not always sufficient to prevent "breakthrough" to lexical access. When this happens, the word stimulus activates a specific response tendency, the word's name. In these circumstances, the system needs to deal with two sources of interference, one at the task level (between naming and reading tasks) and one at the response tendency level (between the name of the colour and the word). Congruent with this account is the observation that more salient words, as for instance words with emotional content, yield larger interference effects (e.g., McKenna & Sharma, 1995; Watts, McKenna, Sharrock, & Trezise, 1986; see also for related findings Jones-Chesters, Monsell, & Cooper, 1998). Due to the high emotional salience of these words, the reading task is less efficiently suppressed, and the word is activated at the response tendency level. The prediction of this account in relation to the distractor frequency effect, however, is less straightforward. As mentioned earlier, when the suppression of the task of reading does not work sufficiently, the word's name becomes activated. This generates an inappropriate response, and therefore, the response selection stage has to reinitiate the generation of the appropriate colour name response. Monsell and colleagues suggest that the occasional generation of an inappropriate response happens faster for high-frequency words. Therefore, one could expect less interference with high-frequency words than with low-frequency words (see Monsell et al.,

2001, p. 148). At the same time, low-frequency words can be considered more salient (e.g., Glanzer & Adams, 1990; Malmberg & Nelson, 2003; Shiffrin & Steyvers, 1997), and therefore, it should be harder to suppress them at the task set of reading filter. If this were the case, low-frequency words would be more prone to generate a response tendency, and, as a consequence, more interference would be expected.

In sum, although most of the studies have detected a distractor frequency effect in the colour-naming Stroop task, there are some inconsistencies in the literature. Here we seek to provide further experimental evidence on the influence of word frequency in the colour-naming Stroop task. We do this by taking two novel approaches with respect to the studies considered so far. First, we monitor the ms-to-ms reflections of the word frequency effect through electroencephalographic recordings. This event-related potential (ERP) approach allows us to generate temporally resolved estimates of the processing taking place during the distractor frequency effect. Second, whereas there are no ERP studies exploring the frequency effect on the colour-naming paradigm, there does exist a rich tradition of ERP studies on the “standard” Stroop effect that have converged on a set of temporal landmarks reflecting processing occurring at various stages in the Stroop paradigm (e.g., Hanslmayr et al., 2008; Liotti, Woldorff, Perez, & Mayberg, 2000; West & Alain, 1999). In the current study, we aim to take advantage of this tradition to explore the distractor frequency effect and compare it with these known temporal landmarks in the context of the Stroop task.

1.1. Experimental overview

In the study reported here, participants were exposed to single, homogeneously coloured words. In half of the trials (i.e., Stroop trials), coloured words were colour names. Stroop trials were congruent or incongruent, based on the word–ink relation. In the other half of the trials (i.e., Frequency trials), coloured words bearing no semantic or phonological relationship with colour names were manipulated for lexical frequency, with half of these trials composed of high-frequency words and the other half composed of low-frequency words. Behaviourally, the expected modulations are a Stroop effect on Stroop trials (i.e., slower colour-naming times on incongruent relative to

congruent trials). In addition, we expected to replicate the Burt (1994, 1999, 2002; see also Dewhurst & Barry, 2006) distractor frequency effect with slower colour-naming times for low-frequency words relative to high-frequency words (see however, Geng et al., 2014). Later, we detail three predictions in relation to the electroencephalographic data.

Interestingly, under experimental conditions in which the frequency of target words is manipulated, brain activity differentiates high- and low-frequency words at very early time windows. For instance, Hauk and Pulvermüller (2004) reported that low-frequency target words elicited more positive occipito-parietal ERP responses relative to high-frequency target words in a 150–190 ms time window (see also Cuetos, Barbón, Urrutia, & Domínguez, 2009; Sereno, Rayner, & Posner, 1998). The first empirical question of the present study is whether an analogous early effect of word frequency would be found if words are distractors, that is under conditions in which the cognitive system should be set to filter out words as potentially interfering stimuli. Critically, Stroop studies have not reported differences in such an early time window, and no differences between congruent and incongruent trials are expected.

Second, it is a reliable phenomenon that ERPs time locked to incongruent Stroop stimuli are characterised by a greater, anteriorly distributed, negativity in a 350–500 ms time window relative to congruent Stroop stimuli (e.g., Liotti et al., 2000; West, 2003; West & Alain, 1999). This ERP deflection has been interpreted in terms of resolution of the response conflict via suppression of the word response in the incongruent condition, and it is independent of response modality (i.e., oral or manual; Liotti et al., 2000). In accordance with this evidence, we expected to replicate this ERP deflection in the Stroop condition, that is the condition generating slower response latencies (i.e., incongruent) should elicit a negative shift of amplitudes relative to the condition generating faster naming latencies (i.e., congruent). In relation to the Frequency condition, studies looking at frequency effects of target words have reported that the early ERP effect (i.e., within 200 ms after word presentation) extends up to ~400 ms (e.g., Cuetos et al., 2009; Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Hauk & Pulvermüller, 2004; King & Kutas, 1998). A further empirical question is therefore whether the continuation of the word (target) frequency effect would be found when words are distractor stimuli. Critically, this

temporal landmark (~400 ms) overlaps with the ERP deflection that indicates suppression of the word response in the “standard” Stroop condition. Thus, an additional scenario would be a similar pattern in Frequency trials to the one obtained in Stroop trials, that is responses in the Frequency condition that generate slower naming latencies should elicit a negative shift of amplitudes relative to the Frequency condition that generates faster naming latencies.

And third, as further support for the reliability of the temporal characterisation of the distractor frequency effect offered by the present investigation, we also monitored a later (i.e., from 500 ms on) occipito-parietal ERP effect observed in the context of the Stroop task, namely the late positive component (i.e., LPC), which is of greater amplitude for incongruent than for congruent Stroop stimuli. LPC deflections have been interpreted as semantic re-elaboration of the meaning of the words (Liotti et al., 2000; West & Alain, 1999; Zurrón, Pouso, Lindín, Galdo, & Díaz, 2009). We expect to observe such ERP modulation in the Stroop trials but not in the Frequency trials, since in these latter trials high- and low-distractor words were semantically neutral in relation to the colour response (i.e., there is no need for re-elaboration of the meaning of the high- and low-distractors words).

1.2. Implications for models of speech production

In recent decades, researchers have developed several Stroop-like chronometric paradigms to describe how lexical retrieval is achieved during speech production (for an extended discussion about the implications of Stroop effects for models of speech production, see Mahon, Garcea, & Navarrete, 2012; Mahon & Navarrete, 2014; Mulatti & Coltheart, 2012; Roelofs, 2003). One of the most commonly used paradigms is the picture-word interference task, in which participants name real-world concepts' pictures while ignoring the presentation of distractor words. One well-established finding using this task is that picture-naming latencies vary as a function of the relationship between picture names and distractor words. For instance, compared to unrelated baseline conditions, picture-naming latencies (e.g., “car”) are slower in the context of semantic coordinate distractor words (e.g., truck) but faster in the context of other semantically related

distractor words (e.g., bumper). Unfortunately, and despite the rich tradition in picture-word interference research, the precise characterisation of the interaction between distractor word and target lexicalisation is still a matter of debate (for recent discussion, see Spalek, Damian, & Bölte, 2013). Recently this debate has been fuelled by the observation that picture-naming latencies are faster in the context of high-frequency distractor words than in the context of low-frequency distractor words (Dhooge & Hartsuiker, 2010, 2011; Miozzo & Caramazza, 2003). Since theoretical models of lexical access make different predictions with reference to the manipulation of the lexical frequency of distractor words, the distractor frequency effect in the picture-word interference task has relevant theoretical implications.

For instance, competitive models hinge on the idea that selecting a target word is determined by the relative activation of the target word and that of the cohort of concurrently activated non-target words: Lexical selection of the target word in this view is less efficient, the higher the level of activation of non-target words (e.g., Levelt, Roelofs, & Meyer, 1999). On the premise that high-frequency words have higher resting lexical levels of activation relative to low-frequency words, competitive models predict slower picture-naming latencies with high-frequency distractor words relative to low-frequency distractor words. A different theoretical proposal assumes instead that lexical retrieval is a non-competitive process and that it is determined only by the level of activation of the target word (e.g., Caramazza, 1997; Dell, 1986; Rapp & Goldrick, 2000). Consequently, according to this latter class of models, no distractor word frequency on naming latencies is predicted, as the only relevant factor influencing lexical selection is the activation of the picture name. The implications of our findings for competitive and non-competitive models of lexical access in speech production are discussed in the general Discussion section.

2. EXPERIMENT

2.1. Method

2.1.1. Participants

Twenty native Italian speakers (7 male) students at the University of Padova took part in the experiment in exchange for course credits. Participants were right-handed, without a history of

neurological or motor deficits, and had normal or corrected-to-normal vision. All participants gave their informed consent according to the ethical principles approved by the University of Padova. The data of three subjects were removed from analyses because of an excessive rate (higher than 30% of trials) of electroencephalography (EEG) artefacts.

2.1.2. Materials

Frequency trials composed of 60 Italian words were selected from the Bertinetto et al. (1995) corpus. Half were high-frequency words (mean counts per million = 1278.2; range = 734–2733) and the other half low-frequency words (mean counts per million = 2.3; range = 1–4, $t(58) = 13.84$; $p < .001$). High-frequency and low-frequency words were matched for the number of syllables (2.7 and 2.9, respectively, $t(58) < 1.03$; $p = .31$) and letters (6.7 and 6.7, respectively; $t < 1$). There was no phonological overlap between the onset of the words and the onset of the colour names. Words were printed in each of the four possible (equiluminant, 34 cd/m²) ink colours (i.e., blue, green, red and yellow) and displayed against a grey background (8 cd/m²). Stroop trials were generated by combining, in half of the trials, semantically congruent words/colours and semantically incongruent words/colours, in the other half of the trials. Frequency trials were generated by displaying each word with each ink colour one time. Ink colours were represented equally in Stroop and Frequency trials and in each of the four experimental conditions (i.e., congruent, incongruent, high-frequency and low-frequency). Frequency and Stroop trials were organised in separate blocks, with 4 blocks of 60 Frequency trials and 4 blocks of 60 Stroop trials. Within each block, trials were randomised within the constraint that no more than four same-colour trials could be displayed in succession. In Stroop blocks, the ink colour on trial n never corresponded to the ignored distractor word of the trial $n - 1$, so as to minimise contamination by negative priming effects. The order of administration of Frequency and Stroop blocks was randomised for each participant, with half of the participants starting with a Frequency block and the other half with a Stroop block. Participants ran through a training phase in which 10 Stroop trials and 10 Frequency trials were randomly intermixed. Frequency trials used in the training phase were not represented during the experimental phase.

2.1.3. Procedure

On each trial, a fixation cross was displayed at the centre of a cathode ray tube monitor for 2000 ms, followed by a coloured word for 1500 ms. Participants were seated approximately 60 cm from the screen. Participants were instructed to name the colour of the ink as fast and as accurately as possible while ignoring the word. Naming latencies corresponded to the time interval between the stimulus' appearance and the onset of the verbal response. Stimulus presentation and response times (RTs) were controlled by E-Prime 2 (Psychology Software Tools, Inc., Sharpsburg, PA).

2.2. EEG recording

EEG activity was recorded continuously by 64 Ag-AgCl electrodes mounted on an elastic cap according to the extended 10–20 system and referenced to the left earlobe. Horizontal electro-oculography (HEOG) was recorded bipolarly from electrodes positioned lateral to the outer canthi of both eyes. Vertical EOG (VEOG) was recorded bipolarly from two electrodes, one above (Fp1) and one below the left eye. EEG, HEOG and VEOG signals were amplified, filtered using a bandpass of 0.01–80 Hz and digitised at a sampling rate of 250 Hz. Impedance at each electrode site was maintained below 5 k Ω . The EEG was re-referenced offline to the average of the left and right earlobes. The EEG was segmented into 700 ms epochs starting 100 ms prior to the onset of the stimuli. Epochs at each electrode site were baseline corrected based on the mean activity during the 100 ms pre-stimulus period. All trials containing eye movements and other artefacts (signals exceeding $\pm 50 \mu\text{V}$ within an epoch, 6.05%) and incorrect responses in the colour-naming task (3.7%) were excluded from the analysis. Previous ERPs studies on overt naming tasks assume that motor artefacts occur after the onset of the verbal response, and that analysing the ERPs before vocal response would result in artefact-free ERPs (Christoffels, Firk, & Schiller, 2007; Koester & Schiller, 2008; for a revision, see Ganushchak, Christoffels, & Schiller, 2011). Here we adopted a similar strategy developed recently by Strijkers, Costa, and Thierry (2010), and we excluded from analyses colour-naming latencies faster than 600 ms (16.7%) to avoid contamination of the ERPs caused by articulatory activity. Following artefacts and error rejection, separate average waveforms for each condition were computed.

2.3. EEG analysis

Electrode sites were clustered in the following regions of interest (ROIs): left frontal (F1, F3 and F5), right frontal (F2, F4 and F6), left fronto-central (FC1, FC3 and FC5), right fronto-central (FC2, FC4 and FC6), left central (C1, C3 and C5), right central (C2, C4 and C6), centro-parietal (Cz, CPz and Pz), left centro-parietal (CP1, CP2 and CP3), right centro-parietal (CP2, CP4 and CP6), left parietal (P1, P3 and P5), right parietal (P2, P4 and P6), left parieto-occipital (PO3, PO7 and O1) and right parieto-occipital (PO4, PO8 and O2). In accordance with the predictions discussed in the Introduction section, we focus on the three critical time windows, from the onset of the stimuli, in which ERPs differentiated between congruent and incongruent trials (in the Stroop condition) and high-frequency and low-frequency trials (in the Frequency condition). These time windows included an early effect (i.e., 160–220 ms) in the Frequency condition at parietal-occipital ROIs (i.e., left parietal, left parieto-occipital, right parietal and right parieto-occipital); a mid-latency effect (i.e., 300–400 ms) both in the Frequency and Stroop conditions at frontal-central ROIs (i.e., left frontal, left fronto-central, left central, right frontal, right fronto-central and right central); and a late effect (i.e., 500–600 ms; the LPC component) in the Stroop condition at parietal-occipital ROIs. We first reported net effects (i.e., p -values) separately per Stroop and Frequency conditions in each ROI and time window. Then, specific analyses were computed in order to test our predictions on the three critical time windows. For each time window, the analyses of variance considered ROIs and Frequency or Stroop as within-subject factors. The Greenhouse–Geisser correction for non-sphericity was applied when appropriate.

2.4. Results

2.4.1. Behavioural data

2.4.1.1. Frequency trials. Four types of responses were excluded from the analyses of RTs: (1) verbal disfluencies (e.g., stuttering and utterance repairs), (2) responses different from the target, (3) RTs less than 250 or greater than 1500 ms and (4) RTs exceeding participant's mean by more than three standard deviations. Mean correct RTs were calculated by participants and items and submitted to statistical analyses using paired sample two-tailed t -tests (t_1 and t_2 , respectively). Colour-naming

TABLE 1

Mean naming latencies (RT), standard deviations (SD) in ms and error percentages (E) for the Frequency and Stroop trials

	RT	SD	E
<i>Frequency manipulation</i>			
High-frequency	730	63	3.2
Low-frequency	753	75	4.1
Effect	23		0.9
<i>Stroop manipulation</i>			
Congruent	739	56	2.2
Incongruent	821	98	5.3
Effect	82		3.1

latencies on low-frequency trials were longer than on high-frequency trials, $t_1(1, 16) = 4.27$, $p = .001$; $t_2(1, 58) = 6.36$, $p < .001$. There was a trend for errors to be more frequent on low-frequency trials than on high-frequency trials, $t_1(1, 16) = 1.51$, $p = .15$; $t_2(1, 58) = 1.75$, $p = .09$. See Table 1.

2.4.1.2. Stroop trials. The same data analyses as in the Frequency condition were conducted here, though subjects were treated only as a random factor (too few items in Stroop trials). Colour-naming latencies on incongruent trials were longer than those on congruent trials, $t_1(1, 16) = 6.85$, $p < .001$. Errors were more frequent on incongruent than on congruent trials, $t_1(1, 16) = 3.87$, $p < .001$. See Table 1.

2.4.2. ERP data

2.4.2.1. Frequency trials. Net Frequency effects (low-frequency minus high-frequency) with their corresponding p -values in each ROI are shown in Table 2.

To test our predictions, frequency effects were computed as the mean difference amplitude values between low-frequency and high-frequency trials for both the early and the mid-latency time windows. Figure 1 shows waveforms time locked to the presentation of low-frequency and high-frequency distractor words for the centro-parietal ROI and voltage topography maps of the early (160–220 ms) and mid-latency (300–400 ms) frequency effects. These effects had a parietal distribution, extending to the occipital electrode sites and to the central electrode sites for early and mid-latency effects, respectively.

In the early time window, the Frequency effect was significant, $F(1, 16) = 4.9$, $p < .05$, $\eta_p^2 = .23$. The interaction between Frequency and ROIs was not significant ($F < 1$). In the mid-latency time

TABLE 2

The magnitude of the Frequency effect (low-frequency *minus* high-frequency) and the Stroop effect (incongruent *minus* congruent) with their corresponding *p*-values of the amplitude variable for the four ERP time windows in each of the ROIs analysed

	160–220 ms		300–400 ms		LPC – 500–600 ms	
	Magnitude	p-values	Magnitude	p-values	Magnitude	p-values
<i>Frequency effect</i>						
Left frontal	0.41	0.14	-0.61	0.08	-0.98	0.04
Left fronto-central	0.47	0.10	-0.83	0.01	-1.03	0.01
Left central	0.47	0.10	-1.01	0.00	-0.83	0.05
Left centro-parietal	0.61	0.04	-1.00	0.00	-0.72	0.10
Left parietal	0.67	0.04	-0.99	0.00	-0.59	0.20
Left parieto-occipital	0.57	0.05	-0.91	0.01	-0.40	0.36
Centro-parietal	0.66	0.07	-0.98	0.00	-0.69	0.13
Right frontal	0.29	0.34	-0.52	0.11	-0.86	0.09
Right fronto-central	0.36	0.25	-0.68	0.03	-0.86	0.04
Right central	0.41	0.19	-0.80	0.01	-0.70	0.10
Right centro-parietal	0.49	0.11	-0.82	0.01	-0.62	0.15
Right parietal	0.61	0.06	-0.71	0.03	-0.34	0.46
Right parieto-occipital	0.54	0.06	-0.51	0.11	-0.09	0.83
<i>Stroop effect</i>						
Left frontal	-0.25	0.40	-0.73	0.05	0.50	0.52
Left fronto-central	-0.15	0.58	-0.75	0.04	1.10	0.16
Left central	0.01	0.96	-0.48	0.17	1.74	0.03
Left centro-parietal	0.16	0.49	-0.38	0.29	2.10	0.01
Left parietal	0.28	0.26	-0.33	0.35	2.58	0.00
Left parieto-occipital	0.21	0.45	-0.45	0.21	2.99	0.00
Centro-parietal	0.16	0.48	-0.58	0.13	2.04	0.02
Right frontal	-0.35	0.21	-1.00	0.02	0.35	0.64
Right fronto-central	-0.26	0.30	-1.04	0.01	0.83	0.28
Right central	0.03	0.91	-0.73	0.05	1.31	0.08
Right centro-parietal	0.15	0.50	-0.66	0.08	1.67	0.03
Right parietal	0.25	0.26	-0.53	0.16	2.21	0.01
Right parieto-occipital	0.30	0.23	-0.41	0.25	2.65	0.00

window, the Frequency effect was significant, $F(1, 16) = 7.13, p < .02, \eta_p^2 = .31$. The interaction between Frequency and ROIs was not significant, $F(2.06, 33.07) = 2.4, p = .11, \eta_p^2 = .13$. Low-frequency distractors elicited more positive amplitudes compared to high-frequency distractors in the early time window, whereas the reverse pattern emerged in the mid-latency time window. A visual inspection of waveforms indicates an additional temporal window (from 450 to 550 ms) in which ERPs differentiated between low-frequency and high-frequency trials. The Frequency effect in this additional window was significant in all ROIs, $F(1, 16) = 11.47, p < .005, \eta_p^2 = .41$. The interaction between Frequency and ROIs was not significant ($F < 1$). This seems to be a continuation of the effect observed at the mid-latency time window.

2.4.2.2. *Stroop trials.* Net Stroop effects (incongruent *minus* congruent) with their corresponding *p*-values in each ROI are shown in Table 2.

Stroop effects were computed as the mean difference amplitude values between incongruent and congruent trials for both the mid-latency and late time windows. Figure 2 shows waveforms time locked to the presentation of congruent and incongruent Stroop stimuli for the left frontal and the left parieto-occipital ROIs and voltage topography maps of the mid-latency (300–400 ms) and late (i.e., LPC) Stroop effects. These effects had fronto-central and parieto-occipital distributions.

In the mid-latency time window, the Stroop effect was significant, $F(1, 16) = 5.89, p < .03, \eta_p^2 = .27$. Incongruent trials were characterised by a negative shift compared to congruent trials. The interaction between Stroop and ROIs was marginally significant, $F(2.04, 32.64) = 2.54; p = .09; \eta_p^2 = .13$, suggesting a trend towards larger Stroop effects in frontal ROIs than in central ROIs (see Table 2). In the late time window (i.e., LPC), the Stroop effect was significant, $F(1, 16) = 13.91, p < .003, \eta_p^2 = .46$, and characterised by a reversed

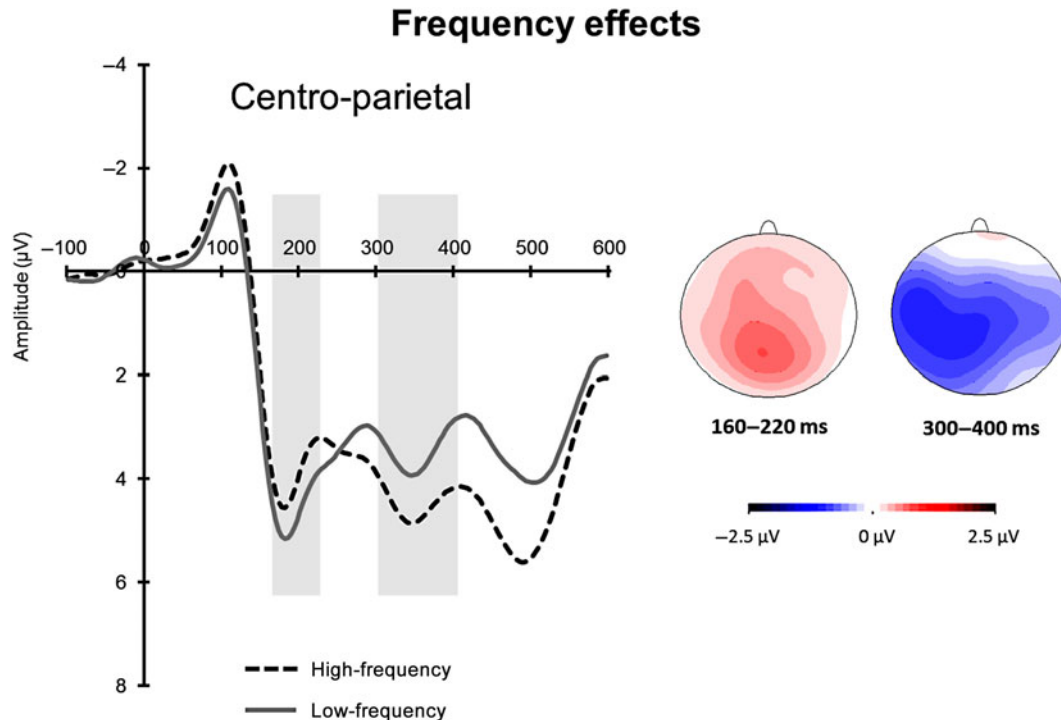


Figure 1. The frequency effect. Low-frequency ERPs compared with high-frequency ERPs at the centro-parietal ROI and the topographic distribution of the effect in the early (160–220 ms) and the mid-latency (300–400 ms) time windows. [To view this figure in colour, please visit the online version of this Journal.]

polarity. The interaction between Stroop and ROIs was significant, $F(1.81, 28.8) = 4.57$, $p < .03$, $\eta_p^2 = .22$, suggesting bigger Stroop effects in occipital ROIs (see Table 2).

3. DISCUSSION

We replicated behaviourally the Stroop effect observing slower colour-naming latencies in the context of incongruent words compared to congruent words. In addition, colour-naming latencies differed as a function of the frequency of the distractor word. In congruence with Burt's studies (1994, 1999, 2002), we obtained slower colour-naming latencies for low-frequency words compared to high-frequency words. ERP differentiated between high- and low-frequency distractor words in an early temporal window (160–220 ms) and in a mid-latency temporal window (300–400 ms). Low-frequency distractors elicited more positive amplitudes than high-frequency distractors in the early temporal window; the reverse pattern was observed in mid-latency temporal window, with a negative shift for low-frequency compared to high-frequency distractors. With respect to ERP modulations in the Stroop task, previous findings were

replicated (e.g., Liotti et al., 2000), showing that congruent and incongruent trials differently modulated ERP amplitudes in the mid-latency (300–400 ms) and LPC (500–600 ms) time windows. The mid-latency Stroop effect was characterised by frontally greater negative amplitudes elicited by incongruent trials than congruent trials, whereas the opposite was observed in the LPC range (posterior distribution), that is incongruent trials elicited greater positive amplitudes than congruent trials.

The finding of an early Frequency effect is congruent with previous studies on word recognition (e.g., Hauk & Pulvermüller, 2004). Here we propose that the early effect (within 200 ms) reflects the processing of the distractor stimuli, that is the response of strongly interconnected neuronal networks that act as memory traces for words; more frequently used words lead to better connected circuits that in turn lead to stronger (or earlier) brain responses (e.g., Shtyrov, Kimppa, Pulvermüller, & Kujala, 2011). The notable aspect of this result is that the effect is shown under conditions in which the lexical status of the word stimuli is irrelevant to performing the task. This early Frequency effect would be congruent with the assumption that there is lexical access to the

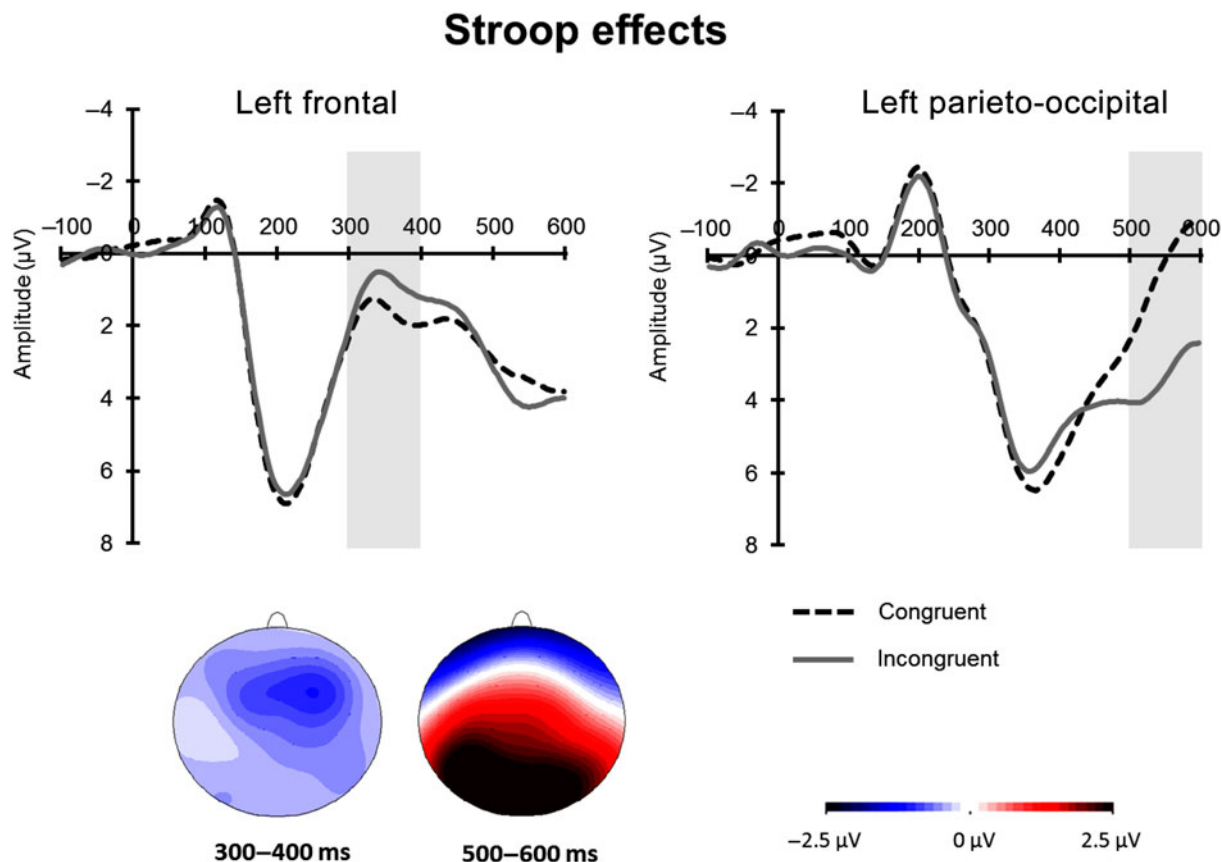


Figure 2. The Stroop effect. Incongruent ERPs compared with congruent ERPs at the left frontal and left parieto-occipital ROIs and the topographic distribution of the effect in the mid-latency (300–400ms) and LPC (500–600 ms) time windows. [To view this figure in colour, please visit the online version of this Journal.]

distractor words in the colour-naming paradigm (Burt, 2002). In relation to the account of Monsell and colleagues (2001), this early effect seems to suggest that the suppression of the task set of reading was not sufficient to prevent “break-through” of the distractor word to lexical activation (i.e., response activation). It is important to remark here that distractor words of the Frequency manipulation were repeated four times during the experiment. Monsell and colleagues have pointed out that word repetition increases the probability of evoking the specific response associated to the word (see however for a distractor frequency effect without word repetition, experiment 4 in Burt, 2002). Further research is needed in order to determine whether the early Frequency effect we reported here is also present without repetition of the distractor words.

The mid-latency Frequency effect would reflect the suppression of distractors in the retrieval of the colour name. This conclusion is in line with the results reported by Liotti and colleagues (2000)

who accounted for the Stroop effect observed in this time window as the resolution of the response conflict, mediated by the anterior cingulate cortex, via the suppression of the word response in the incongruent condition (see also West & Alain, 1999). The mid-latency Frequency effect was characterised by a reversed polarity in comparison to the early latency Frequency effect. Critically, this contrasts with the findings of the studies that explore frequency effects of target words. In these studies, no reverse polarity between early and mid-latency effects is observed. Thus, we conclude that the mid-latency Frequency effect of the present study may reflect the suppression of the word as a possible response, something that is not required in those tasks in which the word is the target, as for instance in a lexical decision task. Comparing Figures 1 and 2, however, it can be seen that even though both the Stroop-like colour-naming and the standard Stroop conditions showed a difference between high- and low-frequency distractors and congruent and incongruent distractors in the 300–

400 ms time window, the distribution of the two effects seems to overlap only partially. The standard Stroop condition showed larger effects at more anterior electrodes with respect to the Stroop-like colour-naming condition, reflecting at least partially independent sources of the effects. This difference is not surprising given that Frequency and Stroop trials differ in several respects. Not only do distractor words have different meanings in the two conditions (i.e. colour names *vs.* words coming from different categories), but they also differ in number (i.e., 4 distractor words repeated several times in the Stroop condition *vs.* 60 distractor words repeated four times in the Frequency condition). We are therefore inclined to conclude that whereas the Frequency and Stroop effects in the mid-latency time window both reflect the suppression of distractors, the differences in the topographic distribution of such effects reflect the specific neural networks involved in Frequency and Stroop trials.

As detailed in the Introduction section, the distractor frequency effect in the picture-word interference and the colour-naming Stroop tasks seems to challenge both theoretical approaches to lexical access (i.e., competitive and non-competitive models of word production). Critically, competitive and non-competitive models obviate the *impasse* of the distractor frequency effect by linking such an effect to mechanisms that are not implicated in lexical access. For instance, the competitive model proposed by Roelofs, Piai, and Schriefers (2011; see also Roelofs, 2005) accounts for the distractor frequency effect by means of an attention mechanism that suppresses distractor words' processing if their activation exceeds a given threshold. In this account, the distractor frequency effect depends directly on the speed with which the distractor word becomes available: As high-frequency words are recognised faster, they will be blocked faster than low-frequency words, yielding less interference. This interpretation assumes that the distractor frequency effect (or part of it) takes place before the lexical selection over the target word begins. This is so because, being high-frequency distractor words more lexically activated than low-frequency distractor words, they would be higher competitors during the lexical selection of the target word (see for further discussion, Finocchiaro & Navarrete, 2013; Scaltritti, Navarrete, & Peressotti, 2014). The early Frequency effect in the colour-naming Stroop task we report here seems congruent with this account. For instance, recent meta-analyses

studies have estimated that lexical selection in speech production takes place between 200 and 400 ms after stimulus onset (Indefrey, 2011; Strijkers & Costa, 2011). According to the suppression mechanism proposed by Roelofs and colleagues (2011), the distractor frequency effect should emerge in a range before the 200 ms after stimulus presentation, as was the case for the early Frequency effect reported here (160–220 ms). Critically, however, after the distractor has been blocked, no frequency effects should be detected anymore; therefore, the distractor frequency effect in the mid-latency time windows we obtain here would be incongruent with this account.

On the other hand, non-competitive interpretations of the distractor frequency effect rest on the assumption of privileged access of distractor words to a post-lexical buffer. A tenet of this interpretation is that this buffer must be freed from distractor words' codes prior to granting access to picture names' codes. In this vein, the sooner the buffer is freed, the faster the code of a picture name can be discharged to overt articulation, which is more likely to occur for high-frequency rather than low-frequency distractor words (Finkbeiner & Caramazza, 2006; Mahon, Costa, Peterson, Vargas, & Caramazza, 2007; Miozzo & Caramazza, 2003; see for a different non-competitive proposal, Dhooge & Hartsuiker, 2010, 2011). According to this view, hence, frequency effects should emerge at a post-lexical level, after 400 ms according to Indefrey (2011) and Strijkers and Costa (2011) meta-analyses studies. Apparently, the pattern we obtain is not compatible with such an approach. However, it is important to remark that the colour-naming paradigm we use in the present study does not allow to tap directly into lexical retrieval processing given that the response set is restricted to four possible words (i.e., the four colour words). Indeed, differently what we reported here, Dhooge, De Baene, and Hartsuiker (2013) recently observed a distractor frequency effect in a late window using a picture-naming task. These authors showed that the distractor frequency effect in the picture-word interference task mainly emerges between 420–500 ms and 520–580 ms. These late effects were interpreted as occurring at post-lexical stages, congruent with non-competitive interpretations of the distractor frequency effect. We consider that the discrepancy between the present study and the one by Dhooge and colleagues may well be due to the different task used. For instance, a critical difference is related to the ease with which the

correct response is retrieved: whereas in colour naming the possible responses are usually three or four colour names (as in the present study), the number of pictures used in the picture-word interference experiments was incomparably higher, making the response highly unpredictable. The two tasks, hence, differ in terms of the relative distribution of resources deployed for controlling the processing of the target and/or the distractor, and this difference might account for the discrepancy observed in the EEG pattern. The present data, therefore, indicate that additional work is required in order to fully understand the nature of the distractor frequency effect obtained with different paradigms (for further discussion, see Geng et al., 2014; Scaltritti et al., 2014).

A different account of the distractor frequency effect in a competitive model has recently been proposed by Starreveld, La Heij, and Verdonshot (2013). According to these authors, the phenomenon may emerge as a consequence of the different recognition thresholds for high- and low-frequency words. Under the assumption that high-frequency words have lower thresholds for recognition than low-frequency words, high-frequency words would reach lower activation than those corresponding to low-frequency words. As a result, the former representations would compete less than the latter ones during the selection of the target word. According to such a view, frequency effects should be evident both early, when the distractor words are recognised, with less activity required for high- than for low-frequency words, and late, at the lexical selection level, where high-frequency words compete less than low-frequency words with the activation of the correct colour response. The both the early and the mid-latency effects we obtain in the present study seem compatible with this account of the distractor frequency effect. As mentioned early, however, further research is needed to understand to what extent the mid-latency in the colour-naming task, with a response set of four words, could reflect lexical retrieval processes as in the standard picture-naming task, where the response set contains tens of words (see Geng et al., 2014; Scaltritti et al., 2014)

4. CONCLUSION

The main conclusion of the present study is that the distractor frequency effect in the colour-naming Stroop task is characterised by two temporally

dissociable ERP effects. Based on previous findings, the two effects might also be functionally dissociable with the first early Frequency effect (160–220 ms) tracking the lexical frequency of the distractor words and the mid-latency Frequency effect (300–400 ms) indicating conflict resolution through distractor word suppression. This last interpretation is suggested by the observation of similar ERP deflections in the mid-latency temporal window (but not in the early temporal window) in the Stroop trials.

REFERENCES

- Bertinetto, P. M., Burani, C., Laudanna, A., Marconi, L., Ratti, D., Rolando, C., & Thornton, A. M. (1995). *CoLFIS (Corpus e Lessico di Frequenza dell'Italiano Scritto)* [Corpus and frequency lexicon of written Italian]. Institute of Cognitive Sciences and Technologies. Retrieved from <http://www.istc.cnr.it/group-page/colfisEng>
- Burt, J. S. (1994). Identity primes produce facilitation in a colour naming task. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*, 47, 957–1000. doi:10.1080/14640749408401103
- Burt, J. S. (1999). Associative priming in color naming: Interference and facilitation. *Memory & Cognition*, 27, 454–464. doi:10.3758/BF03211540
- Burt, J. S. (2002). Why do non-color words interfere with color naming? *Journal of Experimental Psychology: Human Perception and Performance*, 28, 1019–1038. doi:10.1037/0096-1523.28.5.1019
- Caramazza, A. (1997). How many levels of processing are there in lexical access? *Cognitive Neuropsychology*, 14, 177–208. doi:10.1080/026432997381664
- Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event-related brain potential study. *Brain Research*, 1147, 192–208. doi:10.1016/j.brainres.2007.01.137
- Cuetos, F., Barbón, A., Urrutia, M., & Domínguez, A. (2009). Determining the time course of lexical frequency and age of acquisition using ERP. *Clinical Neurophysiology*, 120, 285–294. doi:10.1016/j.clinph.2008.11.003
- Dambacher, M., Kliegl, R., Hofmann, M., & Jacobs, A. M. (2006). Frequency and predictability effects on event-related potentials during reading. *Brain Research*, 1084(1), 89–103. doi:10.1016/j.brainres.2006.02.010
- Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychological Review*, 93, 283–321. doi:10.1037/0033-295X.93.3.283
- Dewhurst, S. A., & Barry, C. (2006). Dissociating word frequency and age of acquisition: The Klein effect revived (and reversed). *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 919–924.
- Dhooze, E., De Baene, W., & Hartsuiker, R. J. (2013). A late locus of the distractor frequency effect in

- picture-word interference: Evidence from event-related potentials. *Brain and Language*, 124, 232–237. doi:10.1016/j.bandl.2012.12.005
- Dhooge, E., & Hartsuiker, R. J. (2010). The distractor frequency effect in picture-word interference: Evidence for response exclusion. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 878–891.
- Dhooge, E., & Hartsuiker, R. J. (2011). The distractor frequency effect in a delayed picture-word interference task: Further evidence for a late locus of distractor exclusion. *Psychonomic Bulletin & Review*, 18(1), 116–122. doi:10.3758/s13423-010-0026-0
- Finkbeiner, M., & Caramazza, A. (2006). Now you see it, now you don't: On turning semantic interference into facilitation in a Stroop-like task. *Cortex*, 42, 790–796. doi:10.1016/S0010-9452(08)70419-2
- Finocchiario, C., & Navarrete, E. (2013). About the locus of the distractor frequency effect: Evidence from the production of clitic pronouns. *Journal of Cognitive Psychology*, 25, 861–872. doi:10.1080/20445911.2013.832254
- Fox, L. A., Shor, R. E., & Steinman, R. J. (1971). Semantic gradients and interference in naming color, spatial direction, and numerosity. *Journal of Experimental Psychology*, 91(1), 59–65. doi:10.1037/h0031850
- Ganushchak, L. Y., Christoffels, I. K., & Schiller, N. O. (2011). The use of electroencephalography in language production research: A review. *Frontiers in Psychology*, 2, 208. doi:10.3389/fpsyg.2011.0208
- Geng, J., Schnur, T. T., & Janssen, N. (2014). Relative speed of processing affects interference in Stroop and picture-word interference paradigms: evidence from the distractor frequency effect. *Language, Cognition, and Neuroscience*, 29, 1100–1114.
- Glanzer, M., & Adams, J. K. (1990). The mirror effect in recognition memory: Data and theory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16(1), 5.
- Hanslmayr, S., Pastötter, B., Bäuml, K. H., Gruber, S., Wimber, M., & Klimesch, W. (2008). The electrophysiological dynamics of interference during the Stroop task. *Journal of Cognitive Neuroscience*, 20, 215–225.
- Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clinical Neurophysiology*, 115, 1090–1103. doi:10.1016/j.clinph.2003.12.020
- Indefrey, P. (2011). The spatial and temporal signatures of word production components: A critical update. *Frontiers in Psychology*, 2, 255. doi:10.3389/fpsyg.2011.00255
- Jones-Chesters, M. H., Monsell, S., & Cooper, P. J. (1998). The disorder-salient Stroop effect as a measure of psychopathology in eating disorders. *International Journal of Eating Disorders*, 24(1), 65–82. doi:10.1002/(SICI)1098-108X(199807)24:1<65::AID-EAT6>3.0.CO;2-Z
- King, J. W., & Kutas, M. (1998). Neural plasticity in the dynamics of human visual word recognition. *Neuroscience Letters*, 244, 61–64. doi:10.1016/S0304-3940(98)00140-2
- Klein, G. S. (1964). Semantic power measured through the interference of words with color-naming. *The American Journal of Psychology*, 77, 576–588. doi:10.2307/1420768
- Koester, D., & Schiller, N. O. (2008). Morphological priming in overt language production: electrophysiological evidence from Dutch. *Neuroimage*, 42, 1622–1630. doi:10.1016/j.neuroimage.2008.06.043
- Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, 22, 1–75.
- Liotti, M., Woldorff, M. G., Perez, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, 38, 701–711. doi:10.1016/S0028-3932(99)00106-2
- MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, 109, 163–203. doi:10.1037/0033-2909.109.2.163
- Mahon, B. Z., Costa, A., Peterson, R., Vargas, K. A., & Caramazza, A. (2007). Lexical selection is not by competition: A reinterpretation of semantic interference and facilitation effects in the picture-word interference paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 33, 503–535.
- Mahon, B. Z., Garcea, F. E., & Navarrete, E. (2012). Picture-word interference and the response-exclusion hypothesis: A response to Mulatti and Coltheart. *Cortex*, 48, 373–377. doi:10.1016/j.cortex.2011.10.008
- Mahon, B. Z., & Navarrete, E. (2014). The CRITICAL DIFFERENCE in models of speech production: A response to Roelofs and Piai. *Cortex*, 52, 123–127. doi:10.1016/j.cortex.2013.12.001
- Malmberg, K. J., & Nelson, T. O. (2003). The word frequency effect for recognition memory and the elevated-attention hypothesis. *Memory & Cognition*, 31(1), 35–43. doi:10.3758/BF03196080
- McKenna, F. P., & Sharma, D. (1995). Intrusive cognitions: An investigation of the emotional Stroop task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 1595–1607.
- Miozzo, M., & Caramazza, A. (2003). When more is less: A counterintuitive effect of distractor frequency in the picture-word interference paradigm. *Journal of Experimental Psychology: General*, 132, 228–252. doi:10.1037/0096-3445.132.2.228
- Monsell, S., Taylor, T. J., & Murphy, K. (2001). Naming the color of a word: Is it responses or task sets that compete? *Memory & Cognition*, 29(1), 137–151. doi:10.3758/BF03195748
- Mulatti, C., & Coltheart, M. (2012). Picture-word interference and the response-exclusion hypothesis. *Cortex*, 48, 363–372. doi:10.1016/j.cortex.2011.04.025
- Rapp, B., & Goldrick, M. (2000). Discreteness and interactivity in spoken word production. *Psychological Review*, 107, 460–499. doi:10.1037/0033-295X.107.3.460
- Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review*, 110(1), 88–125. doi:10.1037/0033-295X.110.1.88
- Roelofs, A. (2005). From Popper to Lakatos: A case for cumulative computational modeling. In A. Cutler (Ed.),

- Twenty-first century psycholinguistics: Four cornerstones* (pp. 313–330). Hillsdale, NJ: LEA.
- Roelofs, A., Piai, V., & Schriefers, H. (2011). Selective attention and distractor frequency in naming performance: Comment on Dhooge and Hartsuiker (2010). *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*, 1032–1038.
- Scaltritti, M., Navarrete, E., & Peressotti, F. (2014). Distributional analyses in the picture-word interference paradigm: Exploring the semantic interference and the distractor frequency effects. *The Quarterly Journal of Experimental Psychology*. Advance online publication. doi:10.1080/17470218.2014.981196
- Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. *NeuroReport*, *9*, 2195–2200. doi:10.1097/00001756-199807130-00009
- Shiffrin, R. M., & Steyvers, M. (1997). A model for recognition memory: REM—retrieving effectively from memory. *Psychonomic Bulletin & Review*, *4*(2), 145–166. doi:10.3758/BF03209391
- Shtyrov, Y., Kimppa, L., Pulvermüller, F., & Kujala, T. (2011). Event-related potentials reflecting the frequency of unattended spoken words: A neuronal index of connection strength in lexical memory circuits? *Neuroimage*, *55*, 658–668. doi:10.1016/j.neuroimage.2010.12.002
- Spalek, K., Damian, M. F., & Bölte, J. (2013). Is lexical selection in spoken word production competitive? Introduction to the special issue on lexical competition in language production. *Language and Cognitive Processes*, *28*, 597–614. doi:10.1080/01690965.2012.718088
- Starreveld, P. A., La Heij, W., & Verdonschot, R. G. (2013). Time course analysis of the effects of distractor frequency and categorical relatedness in picture naming: An evaluation of the response exclusion account. *Language and Cognitive Processes*, *28*, 633–654. doi:10.1080/01690965.2011.608026
- Strijkers, K., & Costa, A. (2011). Riding the lexical speed way: A critical review on the time course of lexical selection in speech production. *Frontiers in Psychology*, *2*, 356.
- Strijkers, K., Costa, A., & Thierry, G. (2010). Tracking lexical access in speech production: Electrophysiological correlates of word frequency and cognate effects. *Cerebral Cortex*, *20*, 912–928. doi:10.1093/cercor/bhp153
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662. doi:10.1037/h0054651
- Warren, R. E. (1972). Stimulus encoding and memory. *Journal of Experimental Psychology*, *94*(1), 90–100. doi:10.1037/h0032786
- Warren, R. E. (1974). Association, directionality, and stimulus encoding. *Journal of Experimental Psychology*, *102*, 151–158. doi:10.1037/h0035703
- Watts, F. N., McKenna, F. P., Sharrock, R., & Trezise, L. (1986). Colour naming of phobia-related words. *British Journal of Psychology*, *77*(1), 97–108. doi:10.1111/j.2044-8295.1986.tb01985.x
- West, R. (2003). Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia*, *41*, 1122–1135. doi:10.1016/S0028-3932(02)00297-X
- West, R., & Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Cognitive Brain Research*, *8*, 157–164. doi:10.1016/S0926-6410(99)00017-8
- Zurrón, M., Pouso, M., Lindín, M., Galdo, S., & Díaz, F. (2009). Event-related potentials with the Stroop colour-word task: Timing of semantic conflict. *International Journal of Psychophysiology*, *72*, 246–252.