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1 **Modulation of parafoveal word processing by cognitive load during**
2 **modified visual search tasks**

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1 **Abstract**

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During visual search for simple items, the amount of information that can be processed in parafoveal vision depends on the cognitive resources that are available. However, whether this applies to the semantic processing of words remains controversial. This work was designed to manipulate simultaneously two sources of cognitive load in order to study their impact on the depth of parafoveal word processing during a modified visual search task. The participants had to search for target words among parafoveally presented semantic, orthographic or target-unrelated distractor words while their electroencephalogram was recorded. The task-related load was manipulated by either giving target words in advance (literal task) or giving only a semantic clue to define them (categorical task). The foveal load was manipulated by displaying either a word or hash symbols at the center of the screen. Parafoveal orthographic and semantic distractors had an impact on the early event-related potential component P2a only in the literal task and when hash symbols were displayed at the fovea, i.e. when both the task-related and foveal loads were low. The data show that all sources of cognitive load must be considered to understand how parafoveal words are processed in visual search contexts.

Keywords: parafoveal processing, working memory load, foveal load, attention, electroencephalography, reading

1 The parafovea is the part of the visual field surrounding the fovea that extends from
2 approximately 2 to 5 degrees of visual angle. It is involved in information pre-processing,
3 attention guidance and saccade programming during various visual activities such as scene
4 exploration, visual search and reading (Rayner, 2009). Parafoveal processing has been well
5 studied in the context of visual search tasks, for which several models have been designed
6 (Deco & Zihl, 2006; Desimone & Duncan, 1995; Wolfe, 2007; Zelinsky, 2008). However, the
7 extension of these models of visual search to more abstract stimuli such as words has been
8 questioned (Léger, Rouet, Ros, & Vibert, 2012; Dampuré, Ros, Rouet, & Vibert, 2014). More
9 generally, the extent to which the cognitive system is able to quickly access and use the
10 meaning of words presented in parafoveal vision during complex tasks such as visual search
11 or reading is a matter of debate.

12 Studies on event-related potentials (ERP) suggest that the meaning of words can be
13 processed rapidly in parafoveal vision. Indeed, words presented in parafoveal vision can
14 modulate ERP components related to semantic processing in reading tasks such as lexical
15 decision (Coulson, Federmeier, Van Petten, & Kutas, 2005; Cristescu & Nobre, 2008) or the
16 sequential reading of briefly presented groups of words (Barber, Ben-zvi, Bentin, & Kutas,
17 2011; Barber, Duñamayor, Kutas, & Münte, 2010; Barber, Van der Meij, & Kutas, 2013;
18 Stites, Payne, & Federmeier, 2017). Several authors were able to observe semantic parafoveal
19 preview benefits during normal reading both in Chinese (Li, Niefind, Wang, Sommer, &
20 Dimigen, 2015; Zhang, Li, Wang, & Wang, 2015; Yan, Richter, Shu, and Kliegl, 2009) and in
21 alphabetic languages (López-Peréz, Dampuré, Hernández-Cabrera, & Barber, 2016;
22 Hohenstein & Kliegl, 2014; Schotter, 2013). Whether parafoveally previewed words are
23 semantically processed during the reading of alphabetic languages would depend on several
24 factors. They include the depth of orthography of the language, the capitalization of the
25 words' first letters, the degree of similarity between preview and target, the predictability of

1 the parafoveal word, but also the current foveal processing load and the amount of attentional
2 resources that are available (Barber et al., 2013; Rayner, Schotter, & Drieghe, 2014; Schotter,
3 2013; Stites et al., 2017). Accordingly, Payne, Stites, and Federmeier (2016) recently
4 demonstrated that manipulating the amount of cognitive resources needed to process the
5 foveal word had an impact on the depth of parafoveal word processing during reading (see
6 also Veldre & Andrews, 2015).

7 To the best of our knowledge, no ERP study has investigated how parafoveal word
8 processing is performed during visual search for words. In this article, we claim that in visual
9 search as during reading, the depth of parafoveal word processing depends on the amount of
10 cognitive resources that are, first, necessary and, second, available to access high-level word
11 representations. In particular, parafoveal semantic processing may depend on (1) how much
12 the features of the parafoveal word are already activated in memory and (2) the different
13 sources of cognitive load associated with the visual search process.

14

15 **Influence of the activated elements in memory on parafoveal processing**

16

17 Models of visual search contend that the items that match the visual or semantic
18 features of the target are fixated more often than target-unrelated stimuli (Harris & Pashler,
19 2004; Huettig, Olivers, & Hartsuiker, 2011; Moores, Laiti, & Chelazzi, 2003; Olivers, Meijer,
20 & Theeuwes, 2006; Soto & Humphreys, 2007). The target template kept in working memory
21 guides the searcher's attention towards the object (Downing, 2000; Harris & Pashler, 2004;
22 Olivers et al., 2006; Soto & Humphreys, 2007; Soto, Heinke, Humphreys, & Blanco, 2005;
23 Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004) or picture (Moores et al., 2003; Telling,
24 Kumar, Meyer, & Humphreys, 2010) that has the most features in common with the target.
25 Then, a saccade is triggered toward the selected item, and a recognition process takes place in

1 order to categorize it as the target or a distractor. At that stage, the distractor items that share
2 features with the target are often fixated for longer durations than unrelated distractors
3 because more time is needed to distinguish them from the target (Becker, 2011; Belke,
4 Humphreys, Watson, Meyer, & Telling, 2008; Meyer, Belke, Telling, & Humphreys, 2007;
5 Potts, Liotti, Tucker, & Posner, 1996). This alternation between early selection and late
6 rejection mechanisms goes on until the target is found (Zelinsky, 2008).

7 Similarly, word processing studies report that people's attention is guided toward the
8 words in the parafoveal visual field that share features with the content of their working
9 memory (Dampuré et al., 2014; Huettig & McQueen, 2007; Huettig et al., 2011; Léger &
10 Tijus, 2007; Léger et al., 2012). During visual search for words, the searcher's gaze is
11 preferentially attracted by words that look like the target word, but also by words that are
12 semantically related to the target word (Léger et al., 2012; Dampuré et al., 2014). Hence, fast
13 lexico-semantic matching between the target template and a semantically-related parafoveal
14 word can occur and is sufficiently efficient to guide the participant's attention. The most likely
15 explanation is that learning the target word before searching for it pre-activates both the
16 meaning and visual form of visually similar words (Boot & Pecher, 2008; Grainger & Jacobs,
17 1996; Rodd, 2004), and pre-activates the lexical representations of the semantic associates of
18 the target word through spreading activation (Heil, Rolke, & Pecchinenda, 2004; Neely,
19 1977). These data suggest that whether or not the meaning of a word seen in parafoveal vision
20 can be grasped depends on the level of pre-activation of the word's representation in memory.

21 According to the ERP literature on visual search for objects or pictures, the
22 comparison between what is perceived and the template stored in working memory is
23 reflected by an early positive ERP component recorded over the frontal scalp regions, the P2
24 or P2a component (Luck & Hillyard, 1994; Potts et al., 1996; Potts & Tucker, 2001; Potts,
25 Patel, & Azzam, 2004). Indeed, this component is modulated by the degree of visual

1 similarity between the target and the stimuli perceived in either the foveal or the
2 parafoveal/peripheral visual field. Recently, Dampuré, Benraiss, and Vibert (2016)
3 demonstrated that during visual search for target words within words presented in the foveal
4 field, the P2a component was also modulated by both visual and semantic similarity of
5 distractors to the target word. In addition, the degree of similarity between the distractors and
6 the target modulated two late ERP components that have been related to word semantic
7 processing. The frontal N300 component would reflect early automatic processing of
8 semantic similarities and/or category membership (Cristescu & Nobre, 2008; Franklin, Dien,
9 Neely, Huber, & Waterson, 2007; Ruz, Madrid, Lupiañez, & Tudela, 2003). The centro-
10 parietal N400 component (Barber et al., 2013; Coulson et al., 2005; Franklin et al., 2007;
11 Kutas & Federmeier, 2011) would reflect the automatic and/or expectation-based spreading
12 activation processes taking place in the mental lexicon.

13 Altogether, the degree of activation in memory of the visual and semantic features of
14 parafoveal words would determine the amount of cognitive resources needed to process them.
15 This implies that the efficiency of parafoveal processing depends on the overall quantity of
16 the cognitive resources available. The next section reviews the main sources of variations of
17 cognitive load that may interfere with parafoveal processing and interact with the degree of
18 activation of the parafoveal words in memory.

19

20 **Influence of various types of cognitive load on attention guidance**

21

22 Since, as stated above, working memory plays a central role in attention guidance, any
23 load imposed on working memory should decrease the efficiency of attention guidance
24 mechanisms and parafoveal processing during visual search for words. This idea has actually
25 been formalized in Lavie's Load Theory of selective attention (De Fockert, 2013; Lavie & De

1 Fockert, 2005), whereby two resource-dependent mechanisms would determine the extent to
2 which a stimulus can be perceived and processed in peripheral vision.

3 The first one is the perceptual selection mechanism, which is a passive, automated
4 selection system that favors foveal processing and will process parafoveal stimuli only if the
5 amount of information to process does not exceed the current capacities. In other words,
6 parafoveal stimuli will be processed only if the foveal perceptual load is low. The mere
7 presence of a stimulus at the fovea is enough to deplete peripheral processing capacities, even
8 when the participants are instructed to ignore the foveal information (Holmes, Cohen, Haith,
9 & Morrison, 1977). In the context of reading, this phenomenon is referred to as the effect of
10 “foveal load” on parafoveal word processing (Henderson & Ferreira, 1990; Hohenstein &
11 Kliegl, 2014; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999), namely the impact of the load
12 associated with the processing of the fixated word on the processing of the word located just
13 on the right of the fixated word. As expressed in Lavie's Load Theory, an increased foveal
14 load would decrease the amount of cognitive resources available for parafoveal word
15 processing (Williams, 1988) and reduce the parafoveal preview effect in reading (for a
16 review, see Rayner, 2009). Accordingly, several word processing studies demonstrated that
17 parafoveal semantic processing can occur when no information must be processed in foveal
18 vision and all cognitive resources can be allocated to parafoveal processing (Calvo & Castillo,
19 2009; Cristescu & Nobre, 2008), or when time constraints are sufficiently low to allow
20 simultaneous processing of both the foveal and parafoveal words (Barber et al., 2013).

21 The second mechanism is a late, active selection mechanism controlled by executive
22 functions. The Load Theory emphasizes the role of working memory, which determines the
23 priorities used to orient processing toward the task-relevant stimuli and avoid the processing
24 of task-irrelevant stimuli (Lavie, Hirst, Fockert, & Viding, 2004). This is highly reminiscent
25 of the role that working memory fulfills in visual search models by keeping in mind the

1 target-template in order to guide attention toward the relevant stimuli. Consequently, a high
2 working memory load should increase distractibility or, in other words, decrease the
3 efficiency of attentional selection. Accordingly, various studies have demonstrated that the
4 visual span, i.e., the region of the visual field from which information can be extracted in a
5 glance (see Rayner, 1998 for a review) decreases when another task must be performed
6 simultaneously (in dual-task paradigms) or when the difficulty of the task increases
7 (Kornrumpf & Sommer, 2015; Pomplun, Reingold, & Shen, 2001). Hence, in the context of
8 visual search, the ability to guide the attention toward relevant, template-matching stimuli
9 also decreases when the working memory load imposed by the task increases (Desimone &
10 Duncan, 1995; Duncan & Humphreys, 1989; Zhang, Zhang, Huang, Kong, & Wang, 2011).

11 Altogether, evidence points toward a simultaneous influence of both the foveal load
12 and working memory load on attentional guidance during visual search. Indeed, in the context
13 of visual search for words, Dampuré et al. (2014) demonstrated for example that the impact of
14 distractor words, which were related either orthographically or semantically to the target
15 word, on attention guidance depended on the nature of the search task. The participants had to
16 search for a target word that was either given before each trial (literal task, Experiment 1) or
17 defined only by its semantic category (categorical search, Experiment 2). The results showed
18 that the searchers' gaze was more attracted by both kinds of distractor words in the literal task
19 than in the categorical task. The categorical task was more difficult, as shown by the time
20 needed to find target words, which was roughly twice longer in the categorical task than in the
21 literal task.

22 From a cognitive point of view, the categorical task has been associated with a higher
23 working memory load because the target template is less well defined than in the literal task,
24 since the participants do not know with certainty which word they are searching for (Schmidt,
25 MacNamara, Proudfit, & Zelinsky, 2014). Indeed, the ability to create and to maintain a

1 stable, well-defined target template in working memory was proven to have a strong impact
2 on attention guidance (Hout & Goldinger, 2015; Wolfe, Butcher, Lee, & Hyle, 2003; Wolfe et
3 al., 2004). In addition, the comparison between the target template and the words perceived in
4 the peripheral visual field requires more cognitive resources in the categorical task because
5 the searcher must access the meaning of each word in the display to decide whether it is the
6 target word, which is not necessary in the literal task.

7 Additionally, Dampuré et al. (2014) demonstrated that within each task, the efficiency
8 of attention guidance depended on the amount of concomitant foveal processing that was
9 needed. In the categorical task for instance, participants' gaze was attracted by distractor
10 words that were related to the target word only at the beginning of the search phase, when the
11 participants were not fixating any word, but not later on in the search phase when they were
12 fixating words in foveal vision.

13

14 **Rationale of the experiment and hypotheses**

15

16 According to the previous sections, the efficiency of parafoveal word processing
17 depends on (1) the working memory load imposed by the task and (2) within each task, the
18 load generated by the current foveal processing. To the best of our knowledge, the present
19 ERP study is the first to investigate the simultaneous impact of both the foveal and working
20 memory loads on the attentional selection of parafoveal words during visual search.

21 With this goal in mind, we modified the experimental design used by Dampuré et al.
22 (2016), in which the participants had to search for a target word among distractor words
23 presented one by one at the center of the screen. The distractor words included “unrelated
24 distractors” that were unrelated to the target word, “orthographic distractors” that looked like
25 the target word and “semantic distractors” that were semantically related to the target word. In

1 the present study, the same words (i.e. the target words and orthographic, semantic and target-
2 unrelated distractors) were presented *in parafoveal vision*, at five degrees of visual angle from
3 the center of the screen, in order to test the efficiency of parafoveal processing.

4 The working memory load was manipulated by varying the nature of the search task.
5 As in Dampuré et al. (2016), participants were instructed to search for target words that either
6 were given in advance (literal task) or defined by their super-ordinate category (categorical
7 task). Because the categorical task generates a higher working memory load than the literal
8 one (Dampuré et al., 2014, 2016; Schmidt et al., 2014; Hout & Goldinger, 2015), more
9 cognitive resources should be available for parafoveal processing in the literal task.

10 Concomitantly, the foveal load was manipulated in both the literal and categorical
11 tasks by varying the nature of the stimulus displayed at the center of the screen (i.e., on the
12 participants' fovea) while the parafoveal words were processed. The foveal stimulus could be
13 either a series of hash symbols or a word unrelated to the target. Since the words were more
14 task-relevant and would be automatically processed (Holmes et al., 1977) even though the
15 participants were instructed not to pay any attention to what appeared in their foveal vision,
16 the foveal load was expected to be higher with the word than with task-irrelevant hash
17 symbols repeated across the entire experiment (Lavie & Robertson, 2001). Hence, more
18 cognitive resources should be available for parafoveal processing when a word rather than
19 hash symbols is present at the center of the screen.

20 The two first hypotheses stated therefore that parafoveal processing should be slower
21 and less accurate in the categorical task than in the literal task (hypothesis 1), and also slower
22 and less accurate when the foveal stimulus is a word rather than hash symbols (hypothesis 2).
23 As a result, the impact of parafoveal orthographic and semantic distractors on error rates and
24 response times compared to parafoveal target-unrelated distractors should be stronger in the
25 literal task than in the categorical task and stronger when the foveal stimulus is hash symbols

1 rather than a word. In addition, in accordance with earlier studies of visual search for words
2 (Dampuré et al., 2014, 2016; Léger et al., 2012) a third hypothesis stated that orthographic
3 and semantic distractors should have a differential impact on error rates and response times,
4 and that this impact should also vary according to the nature of the search task.

5 Regarding the ERP responses, Dampuré et al. (2016) reported modulations of the P2a,
6 N300 and N400 ERP components by orthographic and semantic distractors presented at the
7 center of the screen compared with unrelated distractors. The same three ERP components
8 were targeted in the present experiment in order to be able to compare data from the present
9 experiment with those reported in et al.'s paper. However, because the present experiment
10 was designed to reproduce the parafoveal processing that leads to decide toward which word
11 in the visual field the next saccade will be done during visual search, the participants did not
12 have to identify the parafoveal word, but just to tell whether they believed or not it could be
13 the target. Since in visual search situations, this decision is generally taken within less than
14 400 milliseconds (Dampuré et al., 2014; Léger et al., 2012), the parafoveal orthographic
15 and/or semantic distractors were expected to modulate mostly the frontal P2a and N300
16 components compared to parafoveal unrelated distractors.

17 As stated above, more cognitive resources should be available for parafoveal
18 processing when both the task-related working memory load and the foveal load are low. The
19 fourth hypothesis stated therefore that the strongest modulation of the P2a and N300
20 components by parafoveal orthographic and/or semantic distractors compared to parafoveal
21 unrelated distractors was expected in the literal task and with hash symbols at the center of the
22 screen. Either performing the categorical task or gazing at a word instead of hash symbols
23 was expected to reduce the impact of parafoveal distractors. The parafoveal target-related
24 distractors were expected to have even less or no impact when both the task-related working
25 memory load and the foveal load were high, i.e., in the categorical task and with a word at the

1 center of the screen. Consequently, the modulations of the P2a and N300 components by
2 parafoveal orthographic and/or semantic distractors compared to target-unrelated distractors
3 were expected to be strongly reduced or to disappear in these conditions. As for error rates
4 and response times, an additional fifth hypothesis stated that orthographic and semantic
5 distractors should have a differential impact on ERP components, and that this impact should
6 vary according to the nature of the search task. Altogether, according to hypotheses 4 and 5,
7 the modulations of the P2a and N300 components should result from four-way interactions
8 between the nature of the task, the nature of the foveal stimulus, the target-relatedness
9 condition (target-related distractors versus target-unrelated distractors) and the type of
10 distractor (orthographic or semantic distractors).

11 Finally, a set of experimental displays in which two orthographic or two semantic
12 distractors were displayed simultaneously in foveal and parafoveal vision (see the method
13 section below) was included in the experiment. They were designed to compare the
14 modulations of the ERP components by foveal orthographic and/or semantic distractors
15 compared to foveal unrelated distractors obtained as the participants concentrated on the
16 parafoveal words with the modulations reported by Dampuré et al. (2016) in response to the
17 same foveal distractors presented in isolation. The goal was to ensure that the participants
18 were processing the stimulus appearing at the fovea even when asked to concentrate on the
19 parafoveal words.

20

21

Method

22

23 **Participants**

24

1 Eighteen psychology students (8 women) from the University of Poitiers (France)
2 participated in this experiment. They were all native French speakers, right-handed, with
3 normal or corrected-to-normal vision and were 18 to 33 years old ($M = 23$ years, $SD = 4$). The
4 students were all volunteers and provided their written informed consent before the study.

5

6 **Apparatus**

7

8 All words or symbols were displayed using the E-Prime 1.0 software on a 21-inch
9 screen (resolution 1024 x 768 pixels), in white on a black background and in lowercase 14-
10 point Calibri font. Participants sat comfortably at 60 cm from the screen in a shielded, air-
11 conditioned recording room. Since the human fovea covers about 2° of visual angle (Jacob &
12 Hochstein, 2009), the foveal visual field corresponded to a 21 mm diameter circle on the
13 screen. The electroencephalographic (EEG) signal was collected using an elastic cap
14 containing 64 electrodes arranged in the international 10-20 system and connected to the
15 NeuroScan acquisition system (Compumedics Neuroscan, Abbotsford, Victoria, Australia).

16

17 **Material**

18

19 The experiment included 46 “search trials” (24 experimental search trials and 22 filler
20 search trials) during which participants had to search each time for a particular target word.
21 Half of the search trials took the form of a literal search where the target word was given in
22 advance, whereas the other half of the trials corresponded to categorical searches where the
23 target word was defined by its super-ordinate category.

24 A search trial consisted in finding the target word among a series of parafoveal
25 distractor words presented one by one on successive “search displays” (see Figure 1A). Each

1 search display showed a single word within the participants' parafoveal vision, i.e., five
2 centimeters down from the center of the screen (the "parafoveal word"), and either a series of
3 hash symbols or another word at the center of the screen in the participants' foveal vision (the
4 "foveal stimulus"). Five centimeters represented 4.76 degrees of angle at the viewing distance
5 of 60 centimeters. For each search display, participants were asked to tell whether they
6 believed the parafoveal word might be the word they were looking for or not (see procedure
7 below and Figure 1B) up until the target word appeared.

8 The same words as those used by Dampuré et al. (2014, 2016) were used in this
9 experiment. All the words were French common nouns that contained 2 to 4 syllables, had 4
10 to 10 letters ($M = 7.2$ letters, $SD = 1.4$) and a lexical frequency greater than 1 per million
11 according to the "Lexique 2" database (New, Pallier, Brysbaert, & Ferrand, 2004).

12

13 **Construction of the experimental search displays.** During each of the 24
14 experimental search trial (12 literal search trials and 12 categorical search trials), participants
15 searched for a target word in a sequence of search displays including critical search displays
16 (see Table 1 for examples), plus an additional number of other displays as detailed below. The
17 critical search displays used in each trial included:

18 - Eighteen "target-related" search displays where the parafoveal word was related to the target
19 word and was either a "related orthographic distractor" (ROD, 9 displays) or a "related
20 semantic distractor" (RSD, 9 displays);

21 - Eighteen "target-unrelated" search displays in which the parafoveal word was unrelated to
22 the target word.

23 The RODs were words that shared at least their first and last two letters with the target
24 word, while the RSDs were semantic associates of both the target word and its super-ordinate

1 category (Dampuré et al., 2014). Léger et al. (2012) previously verified the existence of a
2 genuine semantic association between the target word, category name and RSDs.

3 The target-unrelated search displays were created by taking the target-related search
4 displays from another search trial (see Figure 1A for the following explanation). More
5 precisely, the 24 experimental target words were paired in such a way that the 18 critical
6 target-related search displays used during the search trial for a particular target word (say,
7 “Trial A”) were also presented to the same participant during the search trial for *another*
8 target word (say “Trial B”). Because in Trial B the RODs and RSDs were unrelated to the
9 target word, the target-related displays of Trial A became the 18 target-unrelated displays for
10 Trial B. In other words, the RODs and RSDs of Trial A became "unrelated orthographic
11 distractors" (UODs, nine displays) or "unrelated semantic distractors" (USDs, nine displays)
12 in Trial B (for an example, see Table 1). Conversely, the target-related search displays of
13 Trial B were inserted as the target-unrelated search displays in Trial A. As a consequence,
14 each search display related to a particular target word was seen twice by each participant:
15 once during the trial where the participant searched for *this* particular target word, and once as
16 a target-unrelated search display during a trial where the participant searched for *another*
17 target word. This design allowed us to compare the potentials evoked by *the very same search*
18 *displays* in a situation in which the parafoveal words were related to the target word and in a
19 situation in which they were unrelated to the target word (Figure 1A).

20

21

INSERT TABLE 1 ABOUT HERE

22

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24

25

The manipulation across the critical search displays of the orthographic or semantic
relatedness of the parafoveal words with the target word was associated with a manipulation
of the foveal stimulus. Among the nine search displays showing parafoveal words of each of

1 the four categories defined above (i.e., RODs and RSDs in “target-related” search displays,
2 and UODs or USDs in “target-unrelated” search displays), there were three displays where the
3 foveal stimulus was hash symbols, three displays where the foveal stimulus was a neutral
4 word unrelated to any target word (i.e., an “unrelated neutral distractor” or UND), and three
5 displays where the foveal stimulus was another instance of the same type of distractor word as
6 the parafoveal word, e.g., a parafoveal ROD presented together with a foveal ROD (Table 1
7 and Figure 1A). Hence, each experimental search trial included 12 distinct types of critical
8 search displays; the three instances of each type of display showed the same combination of
9 foveal and parafoveal stimuli, i.e., a parafoveal ROD (alternatively UOD, RSD, or USD)
10 displayed together with foveal hash symbols, with a foveal UND, or with a different foveal
11 ROD (alternatively UOD, RSD, or USD). Across the 12 experimental search trials performed
12 in each search condition (literal or categorical), each participant saw 36 search displays
13 showing the same combination of parafoveal distractors and foveal stimuli once in a situation
14 where the distractors were related to the target word (i.e., RODs or RSDs) and once in a
15 situation where they were unrelated to the target word (i.e., UODs or USDs).

16 Nine parafoveal and three foveal RODs (alternatively UODS, RSDs or USDs) were
17 needed to build the critical search displays associated to each pair of experimental target
18 words. Since only six orthographic and six semantic distractors were available for each target
19 word (Dampuré et al., 2016), each distractor was used twice across the experiment (Table 1).

20

21

INSERT FIGURE 1 ABOUT HERE

22

23

24

Additional search displays in experimental search trials. In addition to the 36
critical search displays described above, each experimental search trial included:

1 - The “target display” where the parafoveal word was the target word, which was always the
2 last display of the search trial.

3 - One to six filler displays that showed one parafoveal and one foveal UND. They were
4 introduced randomly in the sequence of displays in order to vary the length of search trials
5 and reduce the possibility of predicting the time of occurrence of the target.

6 - Five other randomly introduced search displays showing secondary targets (i.e., dollar
7 symbols, \$ \$ \$ \$ \$) instead of the parafoveal word. The participants were instructed to press
8 the button referring to a “yes” response when seeing these displays. These secondary targets
9 therefore required a response that was different from that required for the distractors (“no”)
10 and limited the repetition of the same response and the risk that the participants may come to
11 respond “no” increasingly systematically throughout the trial. Moreover, because these
12 secondary targets could appear at any time, the participants had to sustain their attention, even
13 at the beginning of the search trial (see Dampuré et al., 2016).

14 The target word and secondary targets were presented together with either foveal hash
15 symbols or foveal target-unrelated words in order not to promote a response strategy based on
16 the nature of the foveal stimulus.

17

18 **Filler search trials.** As stated above, in addition to the 24 experimental search trials,
19 22 filler search trials were created in order to have search trials of different lengths and further
20 reduce the possibility of predicting the time of occurrence of the target word. These filler
21 search trials included 4 to 38 search displays and were created around target words that were
22 different from those used in the experimental search trials. Hence, the target word could
23 appear as early as in the fourth search display in some trials. The distractor words used in the
24 filler search trials were all unrelated to the target word. However, the proportions of

1 secondary targets and of the different types of foveal stimuli (i.e., hash symbols or words)
2 were the same as in the experimental search trials.

3

4 **Procedure**

5

6 Each participant searched once for each of the 24 experimental target words within the
7 corresponding search trial. The experiment was divided into two sessions of 12 experimental
8 search trials (six pairs of search trials paired together as described above) and 11 filler search
9 trials and lasted for about two hours. One of the sessions took the form of a literal search, with
10 each search trial beginning with the presentation of the exact target word (e.g., search for
11 “corbeau”, *raven* in English). The other session corresponded to a categorical search, in which
12 only the semantic category of the target-word was specified (e.g., search for “un oiseau”, *a*
13 *bird* in English). The order of presentation of the two sessions was counterbalanced between
14 participants and the 12 experimental search trials presented to a given participant in the literal
15 task were presented in the categorical task to the next participant. The order of presentation of
16 the search trials within a session was randomized, as was the order of the search displays
17 within each search trial, with the exception of the target display, which was always presented
18 last.

19 In both tasks, each search display was presented one-by-one for 600 milliseconds.
20 Then, masks automatically replaced both the parafoveal word and the foveal stimulus for
21 1,600 ms (Figure 1). The participants were instructed to fixate the center of the screen but to
22 pay attention only to the word that appeared at the bottom of the screen. For each search
23 display, they had to press a button with the left hand (“no”) if they were certain that the word
24 presented parafoveally was not the target word and to press a button with the right hand
25 (“yes”) in all other cases. They were instructed to avoid any movement such as blinking

1 during the presentation of the words and masks. They were asked to blink only when an
2 asterisk appeared at the center of the screen for 2,000 ms after each masking display and to
3 stop when the fixation cross that preceded the next search display appeared for 1,000 ms.

4

5 **Electroencephalogram (EEG) recording and preprocessing**

6

7 EEGs were recorded via 64 electrodes arranged in the international 10-20 system
8 using the electrode on the left mastoid (M1) as the reference electrode. Eye movements and
9 blinks were recorded using three electrodes, two on the outer canthus of each eye and one in
10 the infra-orbital region of the right eye, thus making it possible to record the electrical activity
11 emitted by the extraocular muscles when the participants made vertical and horizontal eye
12 movements (electrooculogram, EOG). EOG and EEG data were amplified and recorded
13 continuously throughout the experiment using NeuroScan software at a sampling frequency of
14 500 Hz, with an online 0.1-40 Hz band-pass filter. Impedances were kept under 5 k Ω . The
15 data were then processed off-line using Brain Analyzer software (Brain Products GmbH,
16 Gilching, Germany). Processing began by applying a 0.1-30 Hz (24 dB/octave) band-pass
17 filter. The plots were re-referenced offline to average mastoids (M1, M2). The data were
18 segmented from -100 to 2,000 ms relative to the onset of each search display. The 100 ms of
19 recording time before stimulus presentation was used to calculate the baseline.

20

21 **Data Analyses**

22

23 Because the study was designed to assess the rejection of parafoveal distractor words,
24 the search displays in which either the target-word or a secondary target was presented (i.e.,
25 all displays for which participants had to answer “yes”) were not included in the analyses.

1 Similarly, the displays where errors of rejection of parafoveal distractors were made (i.e.,
2 false alarms in which the participant pressed the “yes” button, 9.3% of the cases) or where the
3 participant did not answer (1.2% of the cases) were removed from all analyses.

4 An artifact rejection procedure was then performed to ensure that only the search
5 displays where participants fixated the center of the screen (and not at the parafoveal word
6 located five centimeters below) were included in the analyses. As demonstrated for horizontal
7 eye movements (Stites et al., 2017), Lins, Picton, Berg, and Scherg (1993) showed that there
8 was a linear relationship between the amplitude of vertical eye movements and the size of the
9 corresponding vertical EOG deflection. An eye movement of one degree of visual angle
10 triggers a deflection of about 12 μV . Since in the present experiment, the parafoveal words
11 were displayed at five degrees of visual angle below the central fixation point, a vertical eye
12 movement toward the parafoveal word would produce a vertical EOG deflection of 60 μV . To
13 exclude all trials including sizeable vertical eye movements, an automatic artifact inspection
14 algorithm rejecting any electrical activity outside the -30 μV to 30 μV range was applied to
15 the vertical EOG traces and resulted in the exclusion of 3.2% of the search trials (Figure 2).
16 The plots were then subjected to a thorough visual inspection to reject segments containing
17 other artifacts (e.g., noise, muscle activity, eye blinks, etc.), which resulted in the exclusion of
18 4.1% of the remaining search trials (Figure 2). Overall, 17.8% of the search trials were
19 discarded. In the remaining trials, the average amplitude of vertical EOG deflections was very
20 small ($< 3 \mu\text{V}$), suggesting that participants did not make any saccade to the parafoveal word.

21

22

INSERT FIGURE 2 ABOUT HERE

23

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25

As stated above, the search displays in which two orthographic or semantic distractors
were shown simultaneously in foveal and parafoveal vision were used to check that the

1 participants did process the foveal stimuli. The search displays in which the orthographic or
2 semantic distractors were displayed only in parafoveal vision were used to compare the
3 impact of orthographic and semantic parafoveal distractors with that of target-unrelated
4 distractors according to the nature of the search task (literal versus categorical) and the nature
5 of the foveal stimulus (hash symbols versus target-unrelated words).

6 The impact of the presence of parafoveal orthographic or semantic distractors on error
7 rates and log-transformed response time (i.e. the time that elapsed between the appearance of
8 the stimuli and the moment the participant pressed the response button) was analyzed using
9 respectively a logistic (“logit” package) and a linear (“lmer” package) mixed model
10 implemented in “R” software (version 3.4.0). Both models included Task (literal or
11 categorical), Relatedness condition (target-related or target-unrelated distractors), Type of
12 distractor (orthographic or semantic) and Nature of the foveal stimulus (hash symbols, UND,
13 or another instance of the same type of distractor as the parafoveal word) as fixed factors and
14 Participants and Items as random intercepts. Each model also included as many as possible
15 by-item and by-participant random slopes corresponding to the fixed factors (i.e., Dependent
16 variable ~ Task * Relatedness condition * Type of distractor * Nature of the foveal stimulus +
17 (1 + Task + Relatedness condition + Type of distractor + Nature of the foveal stimulus
18 |Participant) + (1 + Task + Relatedness condition |Item)). The χ^2 and probabilities obtained
19 from the deviance table (Type II Wald χ^2 tests) are reported for error rates, whereas the F
20 values and probabilities obtained from the analysis of the type III variance table using
21 Satterthwaite approximation for degrees of freedom (Satterthwaite, 1946) are reported for
22 response times. Post-hoc pairwise comparisons were based on the adjusted least-squares
23 means and were performed using the “lsmeans” package in “R” software. To control for Type
24 I errors, the Hochberg family wise error correction was applied to p values.

1 A second set of analyses using linear mixed models focused on the amplitudes of the
2 electroencephalographic potentials evoked by the 12 different types of critical search displays
3 defined above. As expected, the visual examination of the grand averages confirmed the
4 presence of the three following components, which were selected for further analysis.

- 5 - A frontal positivity from 140 to 220 ms after word onset, identified as the P2a component.
- 6 - A frontal negativity between 260 and 320 ms, which corresponds to the N300 component.
- 7 - A centro-parietal negativity observed between 450 and 550 ms, which corresponds to the
8 N400 component.

9 Following artifact rejection, the single-trial ERP amplitudes of each one of these four
10 components were extracted for each participant in their respective time windows. Six
11 anatomical regions of interest were defined for ERP analyses (Figure 3), i.e., the antero-
12 frontal (EEG electrodes AF3, AF4, AF7, AF8, F7, F8, AFz), frontal (F1 to F6, Fz), fronto-
13 central (FC1 to FC6, FCz), central (C1 to C6, Cz), centro-parietal (CP1 to CP6, CPz) and
14 parietal (P1 to P6, Pz) regions. Accordingly, the factor Region was included as a fixed factor
15 in the linear mixed models. However, in view of the anatomical distribution of each
16 component on the scalp, the amplitudes of the P2a and N300 components were only analysed
17 over the antero-frontal, frontal, fronto-central and central regions, whereas the amplitude of
18 the N400 component was only analysed over the central, centro-parietal and parietal regions.

19

20

INSERT FIGURE 3 ABOUT HERE

21

22 The linear mixed model obtained for each ERP component included Task, Relatedness
23 condition, Type of distractor, Nature of the foveal stimulus and Region as fixed factors and
24 Participants and Items as random intercepts. Each model also included as many as possible
25 by-item and by-participant random slopes corresponding to the fixed factors (i.e., Dependent

1 variable ~ Task * Relatedness condition * Type of distractor * Nature of the foveal stimulus *
2 Region + (1 + Task + Relatedness condition + Type of distractor + Nature of the foveal
3 stimulus |Participant) + (1 + Task + Relatedness condition |Item)). The F values and
4 probabilities obtained from the analysis of the type III variance table using Satterthwaite
5 approximation for degrees of freedom (Satterthwaite, 1946) are reported. As for the
6 behavioral data, post-hoc pairwise comparisons were based on the adjusted least-square
7 means and were performed applying the Hochberg method for p value adjustment.

8

9 **Results**

10

11 **Error Rates**

12

13 A preliminary analysis showed that the participants missed more parafoveal target
14 words in the categorical than in the literal task (31.9% vs. 11.6%, $\chi^2(1) = 20.60, p < .001$).

15

16 INSERT TABLE 2 ABOUT HERE

17

18 As predicted by hypothesis 1, the logistic mixed model obtained for error rates (Table
19 2) revealed a main effect of Task such that participants made more errors in the categorical
20 task than in the literal task (23.7% vs. 11.3%, $\chi^2(1) = 6.68, p < .01$). There was also an
21 interaction between Task and Nature of the foveal stimulus ($\chi^2(1) = 16.16, p < .001$). In
22 accordance with hypothesis 2, post-hoc pairwise comparisons demonstrated that in the literal
23 task, more errors were made when the foveal stimulus was hash symbols rather than a UND
24 ($b = .34, SE = .12, z = 2.74, p < .01$) or than another instance of the same type of distractor as
25 the parafoveal word ($b = .41, SE = .11, z = 3.60, p < .001$). However, Nature of the foveal

1 stimulus had no significant impact on error rates in the categorical task. Finally, in accordance
2 with hypothesis 3, the model revealed a three-way interaction (Table 2) between Task,
3 Relatedness condition and Type of distractor ($\chi^2(1) = 17.34, p < .001$). The post-hoc pairwise
4 comparisons that were performed using Type of distractor as pivot demonstrated that RODs
5 led to more errors than UODs both in the categorical task ($b = .20, SE = .10, z = 1.97, p < .05$)
6 and in the literal task ($b = 1.14, SE = .12, z = 9.22, p < .001$) and that the impact of RODs was
7 greater in the latter case. In contrast, RSDs led to more errors than USDs in the categorical
8 task ($b = .48, SE = .11, z = 4.50, p < .001$), but not in the literal task ($b = -.08, SE = .14, z = -$
9 $.58, p = .56$).

10

11 **Response times**

12

13 As predicted by hypothesis 1, the linear mixed model obtained for response times
14 (Table 3) revealed a main effect of Task ($F(1, 17) = 23.30, p < .001$) with longer response
15 times in the categorical task ($M = 935$ ms, $SD = 342$) than in the literal task ($M = 685$ ms, SD
16 $= 274$). In accordance with hypothesis 2, there was also an interaction between Task and
17 Nature of the foveal stimulus ($F(2, 605) = 9.27, p < .001$). As for error rates, post-hoc
18 pairwise comparisons demonstrated that in the literal task, response times were shorter when
19 the foveal stimulus was a UND rather than hash symbols ($b = .018, SE = .006, t(130) = 3.04,$
20 $p < .01$) or than another instance of the same type of distractor as the parafoveal word ($b =$
21 $.014, SE = .004, t(130) = 3.09, p < .01$). However, Nature of the foveal stimulus had no
22 significant impact on error rates in the categorical task. Finally, in accordance with hypothesis
23 3, the model revealed a three-way interaction (Table 3) between Task, Relatedness condition
24 and Type of distractor ($F(1, 12,319) = 46.10, p < .001$). The post-hoc pairwise comparisons
25 that were performed using Type of distractor as pivot demonstrated that RODs led to slower

1 response times than UODs in the literal task ($b = .054, SE = .005, t(130) = 11.14, p < .001$)
2 and to marginally slower response times than UODs in the categorical task ($b = .01, SE =$
3 $.005, t(157) = 1.89, p = .06$). In contrast, RSDs led to slower response times than USDs in the
4 categorical task ($b = .018, SE = .005, t(147) = 3.59, p < .001$), but not in the literal task ($b =$
5 $.004, SE = .005, t(115) = .79, p = .43$).

6

7

INSERT TABLE 3 ABOUT HERE

8

9 **ERP results**

10

11 **Analyses of the P2a component (140 – 200 ms).** As predicted by hypotheses 4 and 5,
12 the linear mixed model obtained for the P2a component revealed a four-way interaction
13 between Task, Type of distractor, Relatedness condition and Nature of the foveal stimulus
14 ($F(2, 50,633) = 8.20, p < .001$). Follow-up analyses demonstrated that the three-way
15 interaction between Task, Relatedness condition and Nature of the foveal stimulus was
16 significant for both orthographic ($F(2, 24,513) = 4.28, p < .01$) and semantic distractors ($F(2,$
17 $26,052) = 16.1, p < .001$). The post-hoc pairwise comparisons that were performed using
18 Nature of the foveal stimulus as pivot revealed that in the literal task, but not in the
19 categorical task (Figure 4), RODs evoked a less positive P2a than UODs when the foveal
20 stimulus was either another ROD ($b = -.86, SE = .35, t(225) = -2.49, p < .01$) or hash symbols
21 ($b = -.72, SE = .35, t(237) = -2.04, p < .05$), but not when the foveal stimulus was a UND ($b =$
22 $-.01, SE = .35, t(225) = -.03, p = .98$). In the literal task, RSDs evoked a more positive P2a
23 than USDs (Figure 5) only when the foveal stimulus was hash symbols ($b = 1.02, SE = .33,$
24 $t(211) = 3.14, p < .01$). In the categorical task RSDs evoked a more positive P2a than USDs

1 (Figure 5) only when the foveal stimulus was another RSD ($b = .85$, $SE = .34$, $t(238) = 2.51$, p
2 $< .01$). None of the other post-hoc comparisons was significant (all p values $> .20$).

3
4 INSERT FIGURE 4 ABOUT HERE

5
6 **Analyses of the N300 component (260 – 320 ms).** Again, the linear mixed model
7 obtained for the N300 component revealed the expected four-way interaction between Task,
8 Type of distractor, Relatedness condition and Nature of the foveal stimulus ($F(2, 50,617) =$
9 6.93 , $p < .001$). Follow-up analyses demonstrated that the three-way interaction between
10 Task, Relatedness condition and Nature of the foveal stimulus was significant for
11 orthographic distractors ($F(2, 24,493) = 7.80$, $p < .001$), but not for semantic distractors ($F(2,$
12 $26,065) = 1.74$, $p = .18$). The post-hoc pairwise comparisons that were performed using
13 Nature of the foveal stimulus as pivot revealed that in the literal task, but not in the
14 categorical task (Figure 4), RODs evoked a more negative N300 than UODs when the foveal
15 stimulus was another ROD ($b = -.99$, $SE = .35$, $t(205) = -2.84$, $p < .01$). None of the other
16 post-hoc comparisons was significant (all p values $> .20$).

17
18 INSERT FIGURE 5 ABOUT HERE

19
20 **Analyses of the N400 component (450 – 550 ms).** The linear mixed model obtained
21 for the N400 component revealed a significant main effect of Nature of the foveal stimulus
22 ($F(2, 26) = 30.32$, $p < .001$). Post-hoc pairwise comparisons demonstrated (Figure 6) that the
23 critical search displays evoked a more negative N400 when the foveal stimulus was hash
24 symbols rather than a UND ($b = -1.88$, $SE = .25$, $t(21) = 7.64$, $p < .001$) or than another
25 instance of the same type of distractor as the parafoveal word ($b = -1.59$, $SE = .23$, $t(23) =$

1 6.96, $p < .001$). In addition, the parafoveal distractors evoked a marginally more negative
2 N400 when the foveal stimulus was another instance of the same type of distractor as the
3 parafoveal word rather than a UND ($b = .29$, $SE = .16$, $t(33) = 1.84$, $p = .07$). There was also a
4 marginal main effect of Task ($F(1, 22) = 3.66$, $p = .07$), such that the critical search displays
5 evoked a more negative N400 in the literal task than in the categorical task (Figure 6).

6

7

INSERT FIGURE 6 ABOUT HERE

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9

Discussion

10

11 **Overall impact of the foveal and task-related working memory loads on parafoveal** 12 **processing**

13

14 As expected, the manipulation of the task-related working memory load had a strong
15 impact on the rejection of parafoveal distractor words. Indeed, whatever the foveal stimulus,
16 the categorical task was associated with much slower response times and a larger number of
17 errors of rejection of parafoveal distractors than the literal task. Moreover, the participants
18 missed more parafoveal target words in the categorical than in the literal task. The ERP data
19 revealed that all parafoveal distractors tended to evoke a more negative N400 in the literal
20 task than in the categorical task, which was not the case when they were presented at the
21 participants' fovea (Dampuré et al., 2016). Since the amplitude of the N400 component would
22 reflect the depth of word processing (Chwilla, Brown, & Hagoort, 1995), this suggests that
23 the parafoveal distractors were processed more deeply in the literal task than in the categorical
24 task. Altogether, the results show that in the categorical task, fewer resources would be
25 available for the processing of words in parafoveal vision. The distractor rejection process

1 would be slower and less accurate because more cognitive resources are needed for the
2 maintenance of the target template in memory.

3 In the search displays in which only parafoveal distractors were shown, the
4 manipulation of the nature of the foveal stimulus (i.e., hash symbols versus UND) had an
5 impact on both the duration and accuracy of parafoveal distractor rejection in the literal task,
6 but not in the categorical task. This result suggests that in the categorical task, the task-related
7 working memory load was already maximal, which prevented the manipulation of the foveal
8 load from having a significant impact on error rates and response times.

9 In the literal task, unexpectedly, response times were actually *longer* and error rates
10 *lower* when the foveal stimulus was a UND rather than hash symbols. At first sight, this
11 suggests that parafoveal processing was more efficient when the foveal stimulus was a UND,
12 i.e., in a situation where the foveal load should be higher than with foveal hash symbols and
13 thus in contradiction with Lavie's Load Theory (De Fockert, 2013; Lavie & De Fockert,
14 2005). However, a closer look at the data revealed that in the search displays where the nature
15 of the foveal stimulus was manipulated, most of the errors of distractor rejection observed in
16 the literal task were actually made on parafoveal related orthographic distractors (RODs, see
17 Table 2). Consequently, most of the increase in error rates observed when the foveal stimulus
18 was hash symbols rather than a UND was due to a higher number of errors on RODs, i.e., on
19 words that were visually similar to the target word. Similarly, the increase in the time needed
20 to reject parafoveal distractors observed when the foveal stimulus was hash symbols (see
21 Table 3) was mainly due to a 52 ms average increase in the rejection time of parafoveal
22 RODs. In contrast, the rejection times of the other types of distractors increased by only 4 ms
23 (RSDs) and 22 ms (USDs) or even decreased by 3 ms (UODs).

24 This pattern of results may explain the apparent discrepancy between the data and the
25 hypotheses that were made regarding the impact of foveal load on parafoveal processing.

1 Indeed, according to Dampuré et al. (2016), the identification and rejection of distractor
2 words during visual search tasks involve two separate mechanisms. First, the features of
3 distractor words are used to quickly detect similarities with the target template stored in
4 working memory, and then the distractors that have been preselected based on their visual or
5 semantic similarity with the template are selected for further analysis and ultimately rejected.

6 In the context of the present experiment, the lower foveal load associated with hash
7 symbols would allow participants to more easily detect the visual similarities between the
8 parafoveal distractors and the target compared with when the foveal stimulus is a UND. As
9 stated above, participants had to tell whether they were “certain that the word presented
10 parafoveally was not the target word”. When the foveal stimulus is a UND, participants may
11 be less prone to detect the visual similarity between the target template and RODs, and may
12 thus be more certain that RODs are not the target and must be rejected. In other words, in the
13 high foveal load condition, a higher proportion of RODs would not be preselected for further
14 analysis, despite their visual similarity with the target. Conversely, when the foveal stimulus
15 is hash symbols and the foveal load lower, more cognitive resources may be available to
16 detect the visual similarities between RODs and the target, and more RODs would be
17 preselected for further analysis; this would lead to slower rejection times and more errors of
18 rejection of RODs than when the foveal stimulus is a UND.

19 This interpretation is supported by the ERP data, which show that whatever the search
20 task, parafoveal distractors evoked a more negative N400 when the foveal stimulus was hash
21 symbols rather than a UND or than another instance of the same type of distractor as the
22 parafoveal word. The modulation of the N400 by the nature of the foveal stimulus suggests
23 that in contrast with the meaningless hash symbols, the words presented on the fovea (i.e., a
24 UND or the same type of distractor as the parafoveal word) were semantically processed (e.g.,

1 Kutas & Federmeier, 2011). Hence, these data confirm that more resources were available to
2 process the parafoveal distractors when the foveal stimulus was hash symbols.¹

3 If this interpretation is correct, the lower foveal load associated with hash symbols
4 should allow participants to more easily detect the visual and semantic similarities between
5 the parafoveal distractors and the target. Consequently, the ERPs evoked by parafoveal
6 distractors in the literal task should be more modulated by their orthographic or semantic
7 relatedness to the target when the foveal stimulus is hash symbols rather than a UND. The
8 ERP data reported below confirm this interpretation.

9

10 **Impact of cognitive load on the detection of visual and semantic similarities between the** 11 **parafoveal distractors and the target**

12

13 The respective impacts of the working memory load and foveal cognitive load on the
14 detection of visual and semantic similarities between the parafoveal distractors and the target
15 were tested by observing the ERP components evoked by parafoveal distractors in the search
16 displays in which only parafoveal distractors were present.

17 In the literal task, both parafoveal RODs and RSDs evoked ERP components that were
18 significantly different from those evoked by their respective controls (i.e., parafoveal UODs
19 and USDs), but only when hash symbols rather than a UND were displayed at the center of
20 the screen. This confirms that, as hypothesized in the previous paragraph, the higher error
21 rates and slower response times obtained when hash symbols were displayed at the center of

¹ Close examination of the ERP data revealed that a centro-parietal positivity observed between 310 and 380 ms and identified as the P300 component (see Figure 6) was strongly modulated by the nature of the foveal stimulus ($F(2, 36) = 27.99, p < .001$). The critical search displays evoked a more positive P300 when the foveal stimulus was hash symbols rather than a UND ($b = 1.57, SE = .21, t(25) = 7.42, p < .001$) or than another instance of the same type of distractor as the parafoveal word ($b = 1.53, SE = .23, t(24) = 6.72, p < .001$). Since several authors reported that the amplitude of the P300 component would index the amount of cognitive resources available for monitoring events in the visual periphery (Kramer, Sirevaag, & Hughes, 1988; Polich, 2007), this results confirms that more resources were available for parafoveal processing when the foveal stimulus was hash symbols.

1 the screen were probably due to a better detection of visual similarities between parafoveally
2 presented words and the target template.

3

4 **Parafoveal orthographic distractors.** When the foveal stimulus was hash symbols,
5 parafoveal RODs evoked a less positive P2a than their controls (UODs) in the literal task.
6 Moreover, more errors and longer response times were obtained with RODs than with UODs.
7 In contrast, parafoveal RODs had no impact on the P2a component in the categorical task. In
8 accordance with the hypothesis that the impact of RODs would increase when the task-related
9 working memory load decreases, their impact on error rates and response times was higher in
10 the literal task than in the categorical task.

11 In the literal task, the impact of parafoveal RODs on the P2a component, which would
12 reflect the early detection of similarities with the target template, was actually similar to that
13 of the foveal RODs described by Dampuré et al. (2016). Thus, when both the foveal and task-
14 related working memory loads were low, participants were able to detect the similarities
15 between parafoveal distractors and the target template as well as if the distractors had been
16 presented on the participants' fovea. As discussed more extensively in Dampuré et al., the
17 decrease in P2a amplitude observed in the literal task would reflect the detection of a visual
18 similarity between RODs and target words at a sublexical level (Dambacher, Kliegl,
19 Hofmann, & Jacobs, 2006; Lei, Li, Long, Li, Chen, et al., 2010).

20 In contrast with foveal RODs (see Dampuré et al., 2016), parafoveal RODs did not
21 evoke a more positive P2a than their controls in the categorical task. The absence of
22 modulation of these components by parafoveal RODs in the categorical task suggests that
23 when the task-related working memory load increased, participants failed to detect any
24 similarity between RODs and the target and confirms that in the categorical task, fewer
25 cognitive resources would be available for the processing of parafoveal words.

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Parafoveal semantic distractors. When hash symbols were displayed at the center of the screen, RSDs evoked a more positive P2a than their controls in the literal task only. Compared with USDs, the presence of RSDs was associated with increased error rates in the categorical task but not in the literal task, but the response times were not significantly modified. In accordance with previous visual search studies, which reported that semantic distractors had a weaker impact on attention guidance than orthographic distractors (Dampuré et al., 2014; Léger et al., 2012), parafoveal semantic distractors had a weaker impact on behavioral responses than parafoveal orthographic distractors. The increase in error rates observed in the categorical task is in line with the high proportion of errors made by participants in real categorical visual search tasks (Dampuré et al., 2014; Léger et al., 2012), where semantic distractors are quite often erroneously selected as the target word.

Interestingly, whereas in the present study parafoveal RSDs evoked a more positive P2a than their controls in the literal task only, Dampuré et al. (2016) reported that foveal RSDs evoked a more positive P2a than their controls in the categorical task only. As discussed by Dampuré et al, an increased P2a amplitude would reflect the early detection of a similarity with the target word at a lexico-semantic level rather than at a visual, sublexical level (Baccino & Manunta, 2005; Barber et al., 2013; Blanchet, Gagnon, & Bastien, 2007; Federmeier, Mai, & Kutas, 2005; Lee, Liu, & Tsai, 2012). Hence, this confirms again that the task-related cognitive load is too high in the categorical task to allow efficient parafoveal processing. In the literal task, in contrast, more cognitive resources would be available for the early detection of target-distractor semantic similarity. However, the question arises as to why Dampuré et al. did not find any significant impact of foveal RSDs on the P2a component in the literal task. One explanation may be that when the distractors are presented on the fovea, semantic distractors are not preselected because they do not share any visual feature with the

1 target word. Parafoveal RSDs, in contrast, may need further processing to be rejected based
2 on their visual dissimilarity with the target word.

3 Unlike the foveal RSDs (Dampuré et al., 2016), the parafoveal RSDs did not evoke a
4 less negative N300 than the parafoveal USDs in either the literal task or the categorical task.
5 As discussed by Dampuré et al., the decrease in N300 amplitude observed with foveal RSDs
6 would reflect easier access to word meaning (Cristescu & Nobre, 2008). The meaning of
7 foveal RSDs should be more easily accessed than that of USDs during the search task because
8 the former share semantic features with the target template. The absence of modulation of the
9 N300 component by parafoveal RSDs suggests that participants failed to detect the semantic
10 link between RSDs and the target and confirms that whatever the search task, fewer cognitive
11 resources would be available for parafoveal word processing than for foveal word processing.

12

13 **Potentials evoked by the search displays showing both foveal and parafoveal distractors.**

14

15 As expected, when the word displayed at the center of the screen duplicated the word
16 that was presented parafoveally, the modulations of the P2a and N300 components by
17 orthographic and semantic distractors compared to unrelated distractors became more similar
18 to those obtained by Dampuré et al. (2016) with just the foveal distractors and no word in
19 parafoveal vision. Indeed, in the literal task, the displays showing two RODs evoked a less
20 positive P2a and more negative N300 than those showing two UODs as did foveal RODs
21 compared to foveal UODs in Dampuré et al.'s study, whereas when presented with foveal
22 hash symbols, parafoveal RODs only had an impact on the P2a component compared to
23 parafoveal UODs. Similarly, the displays showing two RSDs evoked a more positive P2a than
24 those showing two USDs in the categorical task as did foveal RSDs compared to foveal USDs
25 in Dampuré et al.'s study, whereas when presented with foveal hash symbols, parafoveal

1 RSDs evoked a more positive P2a than parafoveal USDs in the literal task. Consequently, the
2 data obtained with the displays that included two RODs or two RSDs suggest that despite the
3 instructions to attend only to the parafoveal stimuli, the participants *did* process the stimulus
4 appearing at the center of the screen.

5

6 **Parafoveal and foveal mechanisms of visual search for words**

7

8 Visual search models conceive of the search activity as interplay between two main
9 attentional mechanisms (Deco & Zihl, 2006; Desimone & Duncan, 1995; Wolfe, 2007;
10 Zelinsky, 2008). Attentional guidance mechanisms determine the order in which the different
11 objects present in the visual field are examined according to the number of features they share
12 with the target. Then, once an object is fixated, a recognition mechanism categorizes it as the
13 target or a distractor.

14 In the modified visual search tasks for words used here and by Dampuré et al. (2016),
15 the modulations of the P2a component by orthographic and/or semantic distractors would
16 reflect attentional guidance mechanisms. Fast pre-attentive mechanisms occurring within 200
17 ms after the presentation of words would select the best target candidates based on their visual
18 similarity and/or semantic relatedness with the target template. Indeed, the timing of the P2a
19 component is short enough to make it a relevant marker in the understanding of eye
20 movement control (Reichle, Pollatsek, & Rayner, 2012). The present study complements this
21 picture by showing that the early word selection mechanism that underlies attention guidance
22 and is reflected by modulations of the P2a component can be deployed simultaneously over
23 both the foveal and the parafoveal visual fields. In both parts of the visual field, this
24 mechanism is based on comparisons between the features of the words present in the display
25 and those of the target stored and activated in memory. In addition, the data demonstrate that

1 the efficiency of the detection of similarities between parafoveal distractor words and the
2 target depend on the amount of cognitive resources that are available to process parafoveal
3 stimuli. This extends previous visual search data that demonstrated the sensitivity of
4 attentional guidance mechanisms to cognitive load (Soto et al., 2008; Zhang et al., 2011) to
5 the case of words.

6 More precisely, in accordance with initial hypotheses, the efficiency of attentional
7 guidance mechanisms decreased when the working memory load increased. Indeed,
8 parafoveal distractors were rejected faster and more accurately in the literal task than in the
9 categorical task. In the literal task, the efficiency of attention guidance by parafoveal
10 distractors was also modulated by the amount of cognitive resources used to process the
11 foveal stimuli, i.e., the foveal load. The potentials evoked by parafoveal distractors were
12 impacted by their visual similarity or semantic relatedness with the target only when hash
13 symbols rather than words were displayed at the center of the screen.

14 In contrast with attentional guidance mechanisms, the distractor rejection mechanisms
15 that follow the preselection of distractors for further examination would not reach full
16 efficiency and awareness as long as the distractors are not directly fixated. Indeed, as detailed
17 above, the parafoveal distractor words did not have any impact on the N300 and N400
18 components, which confirms that they were not processed as deeply as when they were
19 presented alone at the participants' fovea (Dampuré et al., 2016). Conversely, the later N300
20 and N400 components would be more related to the distractor rejection mechanisms taking
21 place once a distractor word is fixated.

22 Altogether, present and past studies (Dampuré et al., 2016) point towards a unified
23 conception of the attentional mechanisms used during visual search for visual stimuli (e.g.,
24 objects, words, or pictures). The early attention guidance mechanisms, which are deployed
25 over the whole visual field to detect visual and semantic similarities between what is

1 perceived and the target template, appear to be very sensitive to cognitive load. Despite the
2 fact that these processes do not reach awareness, their efficiency would decrease as the task-
3 related working memory load and/or the foveal load increase. In contrast, the target
4 recognition mechanisms would only reach full efficiency and awareness in foveal vision, in
5 accordance with previous models of visual search (e.g., Zelinsky, 2008) that claim that in
6 natural, speeded search situations, foveal inspection is needed for full, conscious
7 identification of the visual stimuli.

8

9 **Limitations and research perspectives**

10

11 The present data are consistent with most of the gaze number and average gaze
12 duration data obtained in previous eyetracking studies of the impact of orthographic and
13 semantic distractors during actual visual search for words (Dampuré et al., 2014; Léger et al.,
14 2012). However, some of the effects found in actual visual search do not match the present
15 data. In Dampuré et al. (2014), orthographic distractors attracted participants' gaze in the
16 literal task regardless of the type of words they were currently looking at, which suggests that
17 parafoveal orthographic distractors should have a significant impact on the potentials evoked
18 by parafoveal words regardless of the foveal stimulus. Nevertheless, parafoveal orthographic
19 distractors only had an impact on ERP components when hash symbols were displayed at the
20 center of the screen. One possible explanation is that during active search tasks, visual
21 information can be grabbed from various words at each glance, and information about the
22 whole display can accumulate over time (Wolfe, 1994) to be used later in the task. In the
23 present experiment, in contrast, parafoveal processing of distractor words could only be
24 performed once. Another possible explanation may be that in the present experiment,
25 participants engaged in less parafoveal processing of the distractors than when a real saccade

1 is triggered toward them (Deubel & Schneider, 1996), even though similar modulations of the
2 P2a amplitude by parafoveal words were found in active reading-like task (Baccino &
3 Manunta, 2005). This discrepancy between the actual visual search data and the present
4 results questions the transferability of the present data to the situations where multiple words
5 are presented simultaneously in peripheral vision. In other words, how verbal information
6 accumulates over time without awareness and how this impacts eye movements in real visual
7 search tasks must be further investigated.

8 Interestingly, the data are also shedding light on observations made in the context of
9 reading activities. Obviously, visual search for words is quite different from usual reading
10 tasks, in particular because the search task consists mostly in rejecting as quickly as possible
11 the words that are not the target, whereas reading tasks aim at integrating word meanings into
12 an understandable whole. However, recent work suggests that during reading, the amount of
13 processing of parafoveally-previewed words also depends on the current foveal load and
14 available attentional resources (Payne et al., 2016; Rayner et al., 2014; Schotter, 2013). In the
15 present study, lexico-semantic processing of parafoveal words seemed to occur even earlier
16 (i.e., during the first 200 ms) than in reading studies (Barber et al., 2013; Federmeier et al.,
17 2005; Cristescu & Nobre, 2008).

18 Another difference between the reading literature and the present study is that most of
19 the studies that investigated parafoveal word processing in reading manipulated the foveal
20 load by controlling for the lexical frequency of the foveal word. High frequency words
21 decrease the foveal load and increase parafoveal word processing compared to low frequency
22 words (Henderson & Ferreira, 1990; Hohenstein & Kliegl, 2014; Schroyens et al., 1999). In
23 the present study, as in a few reading studies (e.g. Schroyens et al., 1999), the foveal load was
24 manipulated by modifying the relevance of the foveal stimulus for the current task. According
25 to Lavie's Load Theory (Lavie & Robertson, 2001), task-relevant stimuli (i.e., words in the

1 present study) would increase the foveal load compared to task-irrelevant stimuli (i.e., hash
2 symbols or z-strings in Schroyens et al.). Altogether, future studies on the impact of foveal
3 load on parafoveal word processing should take into account the many parameters that may
4 influence foveal load, i.e., the processing difficulty and task-relevance of the foveal stimulus,
5 but also the task-related time constraints. A better knowledge of the word processing
6 principles common to all verbal tasks should pave the way for the elaboration of a unified
7 model of visual word processing (Reichle et al., 2012).

8

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10

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Legends of the figures

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12 **Figure 1. Experimental design.** The first panel (A) shows the different types of search
13 displays that were presented in two paired, randomly presented search trials (i.e., Trial A and
14 Trial B) with the status of the displayed words (i.e., target, R*D for either ROD or RSD, U*D
15 for either UOD or USD, or UND) as a function of the trial in which they were presented (see
16 Table 1 for an example). Note that the 18 critical search displays which show parafoveal
17 distractors (ROD or RSD) related to one of the two target words (say, target A) are presented
18 another time to the same participant during trial B, where they are not related to the target
19 word and thus become UOD and USD, respectively. The second panel (B) shows how each
20 search display was presented and the instructions given to the participant.

21

22 **Figure 2.** Segmented raw vertical EOG data of a rejected trial showing both an eye movement
23 (i.e. a saccade) and a blink.

24

25 **Figure 3.** Representation of the distribution of the electrodes on the scalp and of the
26 topographical variables used for the study of the ERP components.

27

1 **Figure 4.** Potentials evoked in the frontal region of the scalp (Fz electrode) by parafoveal
2 orthographic distractors (RODs, dotted line) and their controls (UODs, solid line) in the literal
3 task and the categorical task as a function of the nature of the foveal stimuli (hash symbols, a
4 UND, or another instance of the same type of distractor as the parafoveal word, i.e., a
5 “repeated distractor”). The smaller frames displayed on some of the panels show the
6 anatomical distribution on the scalp of the significant differences that were found between the
7 P2a (140-220 ms) and N300 (260-320 ms) components evoked by RODs and UODs.

8

9 **Figure 5.** Potentials evoked in the frontal region of the scalp (Fz electrode) by parafoveal
10 semantic distractors (RSDs, dotted line) and their controls (USDs, solid line) in the literal task
11 and the categorical task as a function of the nature of the foveal stimuli (hash symbols, a
12 UND, or a “repeated distractor”). The smaller frames displayed on some of the panels show
13 the anatomical distribution on the scalp of significant differences that were found between the
14 P2a component (140-220 ms) evoked by RSDs and USDs.

15

16 **Figure 6.** Potentials evoked by the critical search displays in the centro-parietal region of the
17 scalp (CPz electrode) as a function of the nature of the foveal stimuli (hash symbols, a UND,
18 or a “repeated distractor”) on the left panel, and as a function of the nature of the search task
19 (literal or categorical) on the right panel. The frames displayed on each panel show the
20 anatomical distribution on the scalp of significant differences that were found for the N400
21 (450-550 ms) component evoked by different types of search displays.

22