ERC Advanced Grant 2016
Research proposal [Part B2]

Part B2: *The scientific proposal* (max. 15 pages)

Section a. State-of-the-art and objectives

From retina to reading
Reading is both a visual and a linguistic skill, and orthographic processing occupies the key interface between visual and linguistic processing (Grainger, 2016; Grainger, Dufau, & Ziegler, 2016). In written languages that introduce extra between-word spacing, words are the buildings blocks of reading, and in those languages that use an alphabetic script, letters are the building blocks of words. Hence the importance of understanding orthographic processing, that is, processing of information about letter identities and letter positions, for understanding reading. Thus, much prior research attempting to link low-level visual processes with higher-level cognitive processes involved in reading has focused on letter-level (e.g., Grainger, Rey, Dufau, 2008) and word-level processing (e.g., Andrews, 2006a). Further key contributions to our knowledge of visual aspects of reading have come from the field of research dedicated to studying eye-movements and sentence reading (see Rayner, 2009, and Radach & Kennedy, 2013, for reviews). However, progress in understanding basic processes in reading has been hampered by limited cross-fertilization of results obtained via these different approaches (Grainger, 2003). In response to this observation, Grainger et al. (2016) outlined a tentative theoretical framework for orthographic processing and reading that was designed to facilitate integration of knowledge accrued via different methodologies. A key feature of the architecture described in Grainger et al. (2016), first proposed by Grainger, Mathôt, & Vitu (2014), is that orthographic information spanning several words (separated by spaces) is processed in parallel and fed into a single channel for subsequent orthographic processing and word identification. This proposal was motivated by recent evidence concerning the spatial integration of orthographic information during sentence reading, and in a novel flanking letters lexical decision task.

Spatial integration of orthographic information
Research on single word reading has mainly focused on how information is integrated over time (*temporal integration*) during the process of word comprehension (Grainger & Jacobs, 1999). Using sophisticated behavioral paradigms, such as masked priming (Forster & Davis, 1984), sometimes combined with electrophysiological recordings, a detailed time-course of component processes (visual, orthographic, phonological, morphological, semantic) has been established (see Grainger & Holcomb, 2009, for review, and Dufau, Grainger, Midgley, & Holcomb, 2016, for a recent study). However, written words are rarely seen in isolation and out of context, yet the influence of neighboring stimuli on visual word recognition has only just started to attract attention. Here the issue is not about how information from prior context is integrated during ongoing word recognition, nor is it about how information from different words is integrated in phrase-level and sentence-level representations during text comprehension. The issues to be examined in the present proposal concern how orthographic information is extracted in parallel from several words, and the consequences of such multi-word parallel processing of orthographic information for skilled reading behavior and reading development. The consequences are described in terms of specific mechanisms for simultaneously extracting orthographic information from several words, and the effects that pooling (spatially integrating) this information might have.

Unlike spoken language, most contemporary writing systems facilitate word segmentation by introducing spaces between words that are larger than the spaces between sub-word units. Word-level representations provide the primary gateway in the transformation of form (orthographic and phonological information) to meaning during skilled reading comprehension.[1] For this to be

[1] I acknowledge the role of phonology (particularly for beginning readers: Share, 1995) and morphology in reading comprehension, but focus here on the most elementary and most fundamental aspect of reading – the processing of orthographic information – that is, information about letter identities and letter positions (Grainger, 2008; 2016).

successful, interference from neighboring stimuli should be kept to a minimum such that only one word is identified at a time, and the meaning associated with that word is integrated within higher-level semantic representations of the text being read. One might therefore expect to see little evidence for spatial integration of orthographic information across neighboring words, since this would only interfere with reading.

However, reading is also a visual skill, and basic visual processing is well known to be prone to the interference caused by spatial integration or pooling, such as the effects of crowding on visual object identification (e.g., Pelli & Tillman, 2008; Whitney & Levi, 2011) including letter identification (e.g., Chanceaux, Mathôt, & Grainger, 2014; Grainger, Tydgat, & Isselé, 2010). Early evidence that some amount of integration of orthographic information occurs across words at different spatial locations was obtained with the letter migration paradigm (McClelland & Mozer, 1986; Davis & Bowers, 2004). More directly relevant for the present proposal is research showing that information extracted from the to-be-fixated parafoveal word influences on-going processing of the currently fixated word (Angele, Tran, & Rayner, 2013; Dare & Shillcock, 2013; Dimigen, Kliegl, & Sommer, 2012), a finding that is in line with prior observations of so-called parafoveal-on-foveal effects during reading (e.g., Kennedy & Pynte, 2005; Kliegl, Nuthmann, & Engbert, 2006). The key difference with respect to older studies is that the more recent studies have shown that orthographic relatedness across the parafoveal and foveal stimuli affects processing of the foveal word. In Angele et al.'s (2013) study, subjects read sentences such as "the store had a coat / coat …", where the 2nd occurrence of "coat" is replaced by the word "sale" when the eyes leave the 1st occurrence of "coat" and cross an invisible boundary, marked by / in the example – the boundary technique (Rayner, 1975). Subjects were faster at reading "coat" in this context compared with a sentence like "the store had a coat / milk …" (with "milk" being replaced by "sale" when the eyes leave "coat").[2] Using the same paradigm, Dare and Shillcock (2013) found facilitation from parafoveal nonword stimuli formed by transposing two letters of the foveal word (e.g., the store had a coat / caot …) compared with a double-substitution control condition (e.g., the store had a coat / ceit …). These results clearly suggest that orthographic information extracted in parallel from the fovea and the parafovea collectively influences the process of foveal word recognition. Further key evidence concerning the spatial integration of orthographic information extracted in parallel from multiple spatially distinct stimuli has recently been obtained from a new paradigm – the "*Flanking Letters Lexical Decision*" (henceforth FLLD) task (see Figure 1).

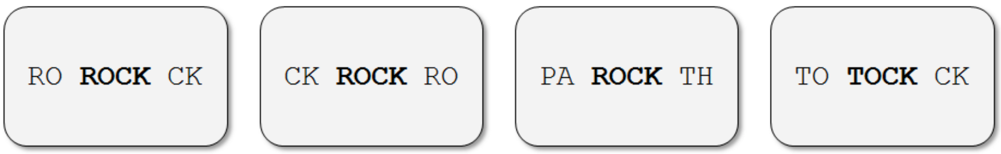

Figure 1. Conditions tested in the Flanking Letters Lexical Decision (FLLD) task in Dare and Shillcock's (2013) study. Subjects respond whether the four central letters displayed in the fovea form a word (e.g., ROCK) or not (e.g., TOCK). Flanking parafoveal letters (dimmed for illustration) can be present in the target in the correct order (RO ROCK CK) or not (CK ROCK RO), or can be different letters (PA ROCK TH). The central target word/nonword is highlighted in order to illustrate the fact that participants are largely unaware of the nature of the flanking stimuli in this paradigm.

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[2] It is crucial to understand the distinction between these parafoveal-on-foveal effects and parafoveal preview benefits. Parafoveal preview experiments measure the influence of a parafoveal "prime" stimulus on processing of a subsequently fixated foveal "target" stimulus at the same spatiotopic location. The observed effects therefore reflect *temporal integration* of information associated with the same spatiotopic location. Parafoveal-on-foveal effects, on the other hand, reflect the *spatial integration* of information across temporally overlapping stimuli at different *spatiotopic locations*. Here I define spatiotopic coordinates for written words as representing the location of a word in a line of text being read independently of the position of the reader's gaze on that line of text.

In the first study to use the FLLD task, Dare and Shillcock (2013) found an influence of the flanking letters on lexical decisions to central target words (faster response times when the letters are the same as in the target: e.g., "RO ROCK CK" vs. "PA ROCK TH"), but more surprisingly they found that the order of the shared bigrams did not matter. Thus lexical decisions to the word ROCK were the same in the following conditions: "RO ROCK CK" and "CK ROCK RO". The starting point of the present project is an explanation for this counter-intuitive finding. The explanation is couched within a new model of orthographic processing and multiple-word reading, which forms the heart of the current proposal. The key finding of Dare and Shillcock (2013) is the equivalent flanker effects found independently of bigram order. Why is this finding important? It is crucially important because no current model of reading would predict such an effect.[3] Furthermore, this finding rules out a simple explanation couched in terms of letter migrations induced by positional noise, since flanker effects have to be greater when bigrams are in the correct order, and this was not the case. This key finding was replicated by Grainger et al. (2014), who further showed that while bigram order is not important, within-bigram letter order is. Thus conditions OR ROCK KC and KC ROCK OR generated significantly less facilitation than RO ROCK CK / CK ROCK RO compared to an unrelated flanker condition.

Theoretical background

Grainger et al. (2014) proposed an explanation for the FLLD results reported by Dare and Shillcock (2013) that builds on Grainger and van Heuven's (2003) model of orthographic processing in which a key distinction was drawn between gaze-centered coding of letter position information and a word-centered relative-position coding mechanism. The extended architecture proposed by Grainger et al. (2014) is shown in Figure 2. The important characteristic of the new architecture, with respect to explaining Dare and Shillcock's (2013) results, is the parallel processing of letters beyond the fixated word, and the mapping of this information onto a single set of word-centered sublexical orthographic representations (implemented as a bag of open-bigrams).

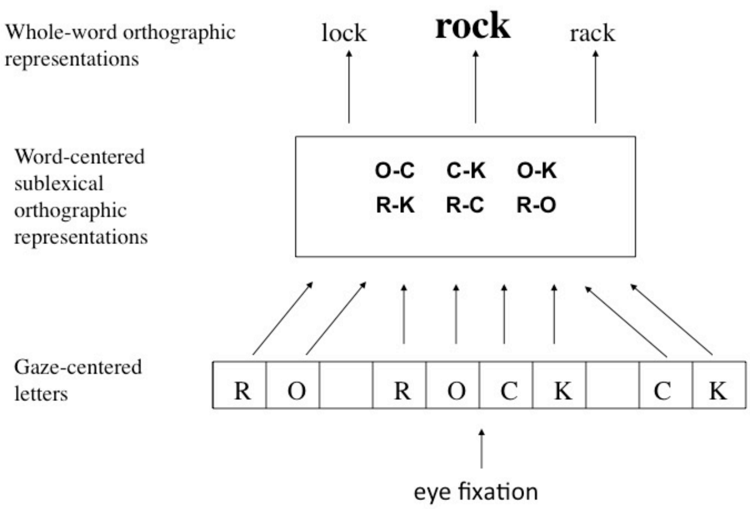

Figure 2. Grainger et al.'s (2014) account of the findings of Dare and Shillcock (2013) obtained with the FLLD paradigm. Gaze-centered letter detectors process letter identities spanning multiple strings and feed-forward activation to an unordered set of contiguous and non-contiguous ordered letter pairs (open-bigrams: Grainger & Whitney, 2004). Bigrams activate whole-word orthographic representations that compete for identification in a winner-take-all architecture.

During fixation of a given word, gaze-centered letter detectors process visual information about the fixated word as well as information to the left and right of that word, within the limits imposed by

[3] A common criticism of research investigating single word recognition is that it does not reflect natural reading. However, in all scientific investigations, laboratory experiments deliberately apply simplified situations in order to provide greater leverage with respect to testing hypotheses. What is crucial is to be able to specify the link between the behavior observed in simplified laboratory tasks and the more complex behavior that occurs in reading outside of the laboratory (Grainger & Jacobs, 1996).

acuity, crowding, and spatial attention (e.g., Legge, Mansfield, & Chung, 2001; McConkie & Rayner, 1975). All activated letter detectors send activation on to all compatible bigram representations in the bag of open-bigrams. The only additional constraint within this single-channel approach to multiple-word reading is that bigrams are only formed within words and not between words. That is, when reading the phrase “grey mouse”, bigrams “g-r” and “g-y” but not “y-m” are activated. This constraint is essential for implementing parallel processing of sublexical orthographic information across several words while limiting, but not completely blocking, the generation of illusory words formed by combinations of letters from different words. Once location-specific letter detectors begin to activate bigram representations, activity in these bigram detectors is then fed-forward to whole-word orthographic representations, which compete with each other for unique word identification via lateral inhibition. Once a word is identified, activity in the corresponding whole-word orthographic representation is suppressed in order to remove interference during processing of the subsequently fixated word. This model therefore enables parallel processing of orthographic information spanning several words while ensuring that only one word is identified at a time.

The model accounts for the results of Dare and Shillcock (2013) because flanking letter pairs will generate activation in bigram representations independently of whether they appear to the left or to the right of fixation. The model predicts, however, that reversing the order of letters within the flanking letter pairs (e.g., “OR ROCK KC”) should make target word recognition harder than when the order is not reversed. This prediction was tested by Grainger et al. (2014). In line with the prediction of their model, they found that target word recognition was significantly slower when within-bigram letter order was reversed in the flanking bigrams compared with the target (e.g., OR ROCK KC; KC ROCK OR), relative to the condition where letter order was the same in flankers and target (RO ROCK CK; CK ROCK RO). On the other hand, and in line with the findings of Dare and Shillcock (2013), the order of flanking bigrams did not significantly affect target word recognition.

Following-up on this initial work, Grainger et al. (2016) proposed a more general theoretical framework for reading research with an aim to provide a theoretical framework that would facilitate integration of findings obtained not only in single word reading research, but also work on eye movements and reading, low-level visual processes involved in reading, and higher-level syntactic and semantic processing. The processing architecture described in Grainger et al. (2016) represents the bridge between the knowledge accrued from the ERC O-code project (2009-14) and the research proposed in the present project. This account of orthographic processing spanning multiple words is most compatible with the class of models of eye-movement control during reading known as “processing gradient” models, with SWIFT being the prime example (Engbert et al., 2005). Nevertheless, the one-word-at-a-time single channel approach that we adopted is also in line with the other major class of models of eye-movement control and reading, “sequential attention shift” models, with EZ-Reader being the prime example (Reichle et al., 1998). Indeed, Angele et al. (2013) have described how evidence for orthographic parafoveal-on-foveal effects can be accommodated within the EZ-Reader framework. In the present project I propose to abandon the single-channel approach.

Beyond a single-channel approach

The model to be implemented and tested in the present project is an extension of the theoretical framework proposed by Grainger et al. (2016). The proposed extension provides an answer to one of the outstanding questions posed by Grainger et al. (2016): *Given the evidence for parallel processing of orthographic information spanning several words, how do readers keep track of which letters belong to which words?* The new model continues to provide an explanation for the evidence in favor of spatial integration of orthographic information spanning several words, while going beyond the single-channel, one word-at-a-time approach to word identification and reading. Yet there are many reasons to favor a single channel approach. First, Occam’s razor pleads in favor of a single-channel approach as the simplest solution. Second, the single channel approach has dominated theorizing on eye-movements and reading and sentence comprehension. Third, a single-channel approach mimics the one-word-at-a-time imposed by the auditory modality in spoken language comprehension. Therefore, we need good reasons to abandon it in favor of a more complex parallel processing approach to orthographic processing and reading.

There are two main sources of evidence against a single-channel approach. The first concerns the growing evidence that *processing of parafoveal words extends beyond the sublexical level* during reading. Although these findings remain controversial, several studies have reported an influence of parafoveal word frequency on eye fixation durations on the foveal word (Kennedy & Pynte, 2005; Kliegl et al., 2006). That is, the frequency of the word immediately to the right (N+1) of the currently fixated word N affects processing of word N. There are also a number of studies showing semantic parafoveal preview benefits during sentence reading (e.g., Hohenstein & Kliegl, 2014; Schotter, 2013; Veldre & Andrews, 2016), and one recent study showing a syntactic preview benefit, whereby preview of a word from a different syntactic category leads to less skipping of the target word (Brothers & Traxler, 2016).

The second source of evidence concerns a phenomenon known as the *"sentence superiority effect"* observed with a novel word-in-phrase identification paradigm. James McKeen Cattell is well-known for having discovered the "word superiority effect" (see Grainger, 2008). What is less well known, however, is that Cattell also discovered a "sentence superiority effect" – that is, he reported that sentences containing up to seven words could be read correctly after one exposure, while the corresponding number of unrelated words was three to four (Cattell, 1886; Scheerer, 1981).[4] Mimicking the important methodological innovation offered by Reicher (1969) and Wheeler (1970) with respect to the word superiority effect, Asano and Yokosawa (2011) investigated the sentence superiority effect with post-cued 4-alternative forced choice following brief presentation of sentences and agrammatical lists of words. Sentences were on average 12-14 Japanese Kanji characters long and were presented for 200 ms and followed by a continuous pattern mask. Targets were 2-character words randomly located at different positions in the sentence, and the four response alternatives were presented vertically aligned below the location of the target word in the sentence. Asano and Yokosawa found that semantic relatedness between words, rather than syntactic structure (grammatically correct vs. illegal word sequences), improved 4AFC accuracy. The lack of a syntactic effect in that study might, however, be due to the specific nature of Kanji (logographic) text that imposes less syntactic constraints compared with alphabetic writing systems. In line with this speculation are the results of (Jordan & Thomas, 2002) who found evidence for effects of syntactic coherence rather than between word semantic priming in word-in-sentence identification, with target words being presented after a sentence context and not simultaneously with the context. Here I propose to build on prior evidence in favor of a sentence superiority effect and to explore this important result using a variant of the paradigm introduced by Asano and Yokosawa, that I will call the "Rapid Parallel Visual Presentation" (RPVP) paradigm.

In sum, there is growing evidence that multiple word identities can be processed in parallel during sentence reading, enabling simultaneous retrieval of semantic and syntactic information from these different words. One central hypothesis of the present project is that readers keep track of the positions of words by associating word identities with ***spatiotopic coordinates*** (world-centered) in short-term memory. Spatiotopic coordinates provide a reference frame for representing the location of an object in a visual scene independently of where the viewer's eyes are looking at the scene. Here I adapt this concept to the case of reading and I define spatiotopic coordinates for written words as representing a word's location in a line of text that is being read, independently of the position of the reader's gaze on that line of text. In line with this proposal is the finding reported by Andrews (2006b) that repetition blindness is largely eradicated when words are presented at different spatial locations. Repetition blindness refers to the diminished ability to identify repeated words in a stream of rapidly presented words using the standard RSVP (rapid serial visual presentation) procedure where words appear sequentially at the same central location (Kanwisher, 1987). Presenting words sequentially but at different locations would enable the use of spatial information to discriminate between word repetitions therefore facilitating the identification of word repetitions (see Grainger, Midgley, & Holcomb, 2016, for an investigation of priming across spatially distinct and temporally non-overlapping stimuli).

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[4] Somewhat less surprising is the fact that a sentence superiority effect is also found in working memory (WM) tasks comparing recall for random lists of words vs. sentences (Baddeley, Hitch, & Allen, 2009). The crucial difference between WM tasks and the RPVP procedure is the amount of time available for processing each word.

Objectives: Parallel Orthographic Processing and Reading (POP-R)

The starting point of the project is the theoretical framework outlined in Grainger et al. (2016), and the current evidence against the single channel approach proposed in this framework. In a nutshell, the project aims to fulfill the overarching goal stated by Grainger et al. (2016), that is to develop and test a computational model of orthographic processing during sentence reading that will facilitate integration of results obtained from the multiple facets of contemporary reading research. In developing this computational model we aim to fill the ***missing link*** between research examining the influence of low-level visual factors and eye-movements during reading and research examining higher-level influences of semantic and syntactic information during text comprehension.

The POP-R model, to be implemented and tested in the present project, is a model of parallel processing of orthographic information spanning several words within the limits imposed by visual acuity, crowding, and spatial attention. It describes how low-level visual processing enables activation of orthographic representations of words and how different word identities are ordered for the purposes of higher-level syntactic and semantic processing. The output of the POP-R model are the ***three ingredients required for successful computation of sentence meaning*** during sentence reading: 1) semantic and 2) syntactic information associated with a given word identity,[5] and 3) information about the position of that word in the sentence (or sentence constituent). POP-R is not a model of eye-movement control during reading, but provides a framework for orthographic processing that can easily integrate current approaches to the control of eye-movements during reading.[6] It is not a model of sentence comprehension, but provides the necessary ingredients – word identities and their ordering – for syntactic processing and semantic integration. It is not a model of reading aloud, but a model of orthographic processing during silent reading for meaning, something most adults do much more often than reading aloud. For this reason, the role of phonology has been ignored in the present proposal (see footnote 1), but is part and parcel of the wider framework (e.g., Grainger et al., 2012), and the inclusion of both sublexical and lexical phonological representations in the full model could be used to implement reading aloud. In spite of these deliberate limitations, the POP-R model nevertheless comprises a highly significant component of the overall network that enables fluent reading for meaning. It forms the very heart of the reading network, performing the core function of mapping visual forms onto linguistic forms that provide the key ingredients for higher-level sentence and text-level comprehension processes. Our long-term goal, beyond the scope of the present project, is to complete the POP-R model with mechanisms for eye-movement control (see footnote 5) and sentence comprehension, while including phonology and morphology as part of the core word reading network.

The project comprises six main objectives. First, the POP-R model will be implemented as a computational model of orthographic processing spanning multiple words, and as a specification of the mechanisms involved in the spatial integration of orthographic information during reading. Second, behavioral FLLD experiments will be run to test the core mechanisms for orthographic processing spanning multiple strings implemented in the POP-R model, and to specify how letter processing across multiple strings differs from processing multiple strings of other kinds of stimuli. Third, EEG and MEG recordings will be combined with the FLLD paradigm in order to specify the spatio-temporal dynamics of spatial integration processes. Fourth, word-in-phrase identification experiments will be run using the novel RPVP paradigm in order to investigate the extent to which word identification can operate in parallel across multiple words. Fifth, sentence reading experiments will be performed with eye movement recordings combined with EEG recordings in order to test specific predictions derived from the multi-channel theoretical framework of the POP-R model. The sixth and final objective is to study the development of parallel orthographic processing in primary school children, and to examine possible links between such processes and reading fluency.

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5 Again, for simplicity, the role of morphemes is ignored here.

6 This proviso is included in order to delimit the scope of the present proposal. In work in collaboration with M. Meeter (VU Amsterdam), to be performed in parallel with the research proposed here, we will include mechanisms for eye-movement control within the framework of the POP-R model. M. Meeter will take the lead in this parallel research project to be performed in collaboration with J. Snell (PhD student currently co-supervised by Grainger and Meeter).

Section b. Methodology

The proposal contains 6 work-packages (WP) each dedicated to one of the 6 major objectives described in Section a, and with each WP containing a certain number of sub-goals linked to specific research questions. Note that in all the experiments to be described in WP 2-6, for each participant we will obtain measures from a battery of tests designed to help reveal potential individual differences in the processing of orthographic information spanning several words and the spatial integration of orthographic information. These will include measures of reading and spelling ability, vocabulary size, visual span, and working memory span (including visual short-term memory).

WP1. Implementation of the POP-R model
Collaborators: Prof. M. Meeter (VU Amsterdam), PhD-1
Major goal: Implement the POP-R model as a computational model of orthographic processing and reading.

The POP-R model incorporates a fan-in-fan-out structure in order to account for spatial integration of orthographic information extracted from multiple words, and yet to still be capable of keeping track of the location of different words. The architecture of the model is shown in Figure 3. It incorporates key features of the architecture described in Grainger et al. (2016), which I will not reiterate here. The main difference with respect to Grainger et al.'s (2016) proposal is that spatial information is now used to track word-in-phrase order. This is achieved via spatiotopic word representations that temporarily associate word identities with a spatiotopic location. The spatiotopic location of a word is defined here as its location in a line of text being read independently of where the reader's eyes are fixating. It is these spatiotopic word representations that provide information about word identity and word-in-phrase position to higher-level sentence comprehensions processes. They provide a short-term memory representation of the spatiotopic location of several word identities that is updated as new words join this short-term store and old words drop out. Spatiotopic word representations are connected to gaze-centered letter detectors via bidirectional connections. This retinotopic-spatiotopic connectivity serves to connect spatially distinct "blobs" in the retinotopic saliency map (cf. Reilly & Radach, 2006) with locations in the spatiotopic map of word identities. The connectivity is re-mapped upon an eye movement in order to maintain the mapping of the same retinotopic blobs onto the same spatiotopic locations while moving the eyes along a line of text. It is the triangular connectivity between retinotopic letters, spatiotopic words, and location-invariant orthographic representations that serves to temporarily bind location-invariant orthographic representations to a specific location in the line of text being read.

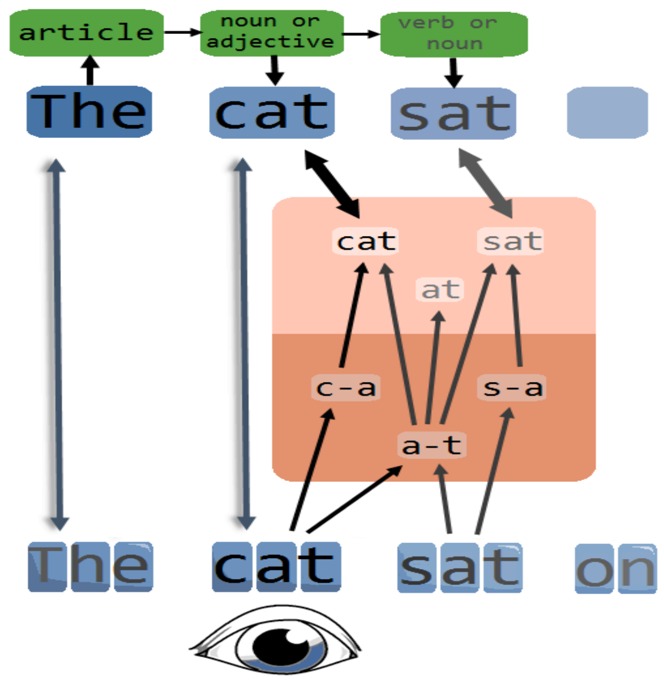

Figure 3. The POP-R model of parallel orthographic processing and reading. Gaze-centered letter detectors (bottom layer) feed-forward activation to word-centered sublexical orthographic representations (c-a, a-t, s-a) that in turn activate whole-word orthographic representations (cat, at, sat). Activated whole-word orthographic representations are associated with a spatiotopic location that is connected with the retinotopic location of the letter detectors that are the source of activation of the word representation. In this way different word identities are temporarily bound to distinct spatiotopic locations in short-term memory.

As underlined in Section a, the POP-R model is not a model of sentence comprehension. The POP-R model outputs the ***three ingredients required for successful computation of sentence meaning*** during sentence reading: 1) semantic and 2) syntactic information associated with a given word identity, and 3) information about the position of that word in the sentence (or sentence constituent). Crucially, the spatiotopic coding of several word identities in POP-R can be used to infer word-in-sentence position (i.e., word order information) using local context. The model will be implemented in a localist connectionist framework (Grainger & Jacobs, 1998) applying the equations of the interactive-activation model (McClelland & Rumelhart, 1981).

WP2. Behavioral measures of spatial integration processes in linguistic and non-linguistic stimuli
Collaborators: Dr. S. Dufau (Aix-Marseille University), PostDoc-1
Major goal: Test predictions of the POP-R model with respect to behavioral flanker effects in linguistic and non-linguistic stimuli.

The POP-R model of orthographic processing and reading builds on Grainger et al.'s (2014) explanation of effects of letter order and bigram order seen in experiments using the FLLD paradigm. The experiments in WP2 provide a further test of this specific explanation of flanking letter effects, and provide a test of the hypothesized locus of such effects as arising at the level of location-invariant sublexical orthographic representations.

2.1 Testing POP-R with FLLD experiments
Specific aim: Provide tests of key predictions of the POP-R model with respect to flanking letter effects obtained in the FLLD paradigm.

Two key findings motivated the development of the theoretical framework for orthographic processing and reading proposed by Grainger et al. 2016 and extended in the POP-R model. One is the lack of an influence of flanker order first reported by Dare and Shillcock (2013). The other is the influence of letter order reported by Grainger et al. 2014. Here I propose two series of experiments - one providing further manipulations of letter order and flanker order, and the other examining the influence of flanker lexicality – as direct tests of predictions derived from the POP-R model. Pilot work suggests that robust flanker effects can be obtained with 6-letter target words flanked by 3-letters to the left and 3 letters to the right, hence providing more degrees of freedom in the manipulation of target-flanker orthographic overlap. I will manipulate the number of flanking letters, whether or not they are formed of letters from the target word and in the correct order or not, and whether or not letter contiguity is maintained across flanker and target. These experiments will also investigate the relative contribution of outer (i.e., first and last) letters in flankers and targets to flanking letter effects.

Does flanker lexicality influence flanking letter effects? According to the POP-R model, identification of the central target word should not be influenced by flanker lexicality. Thus, orthographically related flankers should facilitate target word recognition independently of whether or not they are real words and whether or not they are split across the left and right flanker positions (e.g., LOCK ROCK LOCK; LO ROCK CK; BOCK ROCK BOCK; BO ROCK CK). However, lexical decision responses to the central target could well be influenced by flanker lexicality, via the decision mechanism pooling evidence in favor of a "word" response from both target and flanker stimuli (Dufau, Grainger, & Ziegler, 2012). Therefore, I propose to compare flanker lexicality effects with different tasks performed on central targets; notable lexical decision, semantic categorization (e.g., living vs. non-living), and syntactic categorization (e.g., noun vs. verb).

2.2 Spatial integration of linguistic and non-linguistic stimuli
Specific aim: Compare flanker effects with strings of linguistic stimuli (letters) and non-linguistic stimuli (digits, symbols) in order to specify the locus of spatial integration processes.

Some of the key results that arose from the previous ERC-funded research on orthographic processing of isolated words were obtained by comparing processing strings of letters with strings composed of other kinds of stimuli (see Grainger & Hannagan, 2014, for a review). One paradigm that has proved useful in the context of this endeavor is the same-different (SD) matching paradigm, which enables a comparison across different types of stimuli. Here I propose to use a variant of SD matching with flanking stimuli placed left and right of a central target string. Same-different matching is performed on centrally located targets, and participants are informed that flanking stimuli are to be ignored. Stimuli (4 central characters flanked by 2 characters to the right and to the left) are presented horizontally centered on fixation with the first string presented one line above fixation for 300 ms and the second string one line below fixation until response. Participants decide whether the two central strings are the same or different. Flanking characters can either be repeated from the central string in the correct order (1) or not (2), or formed of different characters (3). The examples are given for a "different" response:

1) DF DFBH BH	2) BH DFBH DF	3) GM DFBH LS
DF DFCH BH	BH DFCH DF	GM DFCH LS

The aim of these experiments is to test whether spatial integration of visual information across multiple groups of elements is a general principle of visual information processing, or whether it is a further specificity of orthographic processing tied to the very nature of location-invariant sublexical orthographic representations. The prediction of the POP-R model is that the key pattern found with word stimuli (RO ROCK CK = CK ROCK RO < PA ROCK ST) will be also found with random consonant strings, but will not be found with strings of symbols or digits. More precisely, I hypothesize that some form of spatial integration operates over visual stimuli independently of their linguistic status or not, but that linguistic stimuli will show a specific pattern of flanker effects that reflects the special way that letter order information is represented.

WP3. Specifying the spatio-temporal dynamics of spatial integration processes
Collaborators: Dr. J.M Badier (Aix-Marseille University), Dr. S. Dufau (Aix-Marseille University), Prof. P. Holcomb (San Diego State University, USA), PostDoc-2
Major goal: Exploit the simplicity of the FLLD paradigm in combination with ERP and MEG recordings in order to specify the spatio-temporal dynamics of the neural activity that underlies spatial integration of orthographic information spanning multiple words during reading.

The same set of flanker conditions will initially be used in both the ERP and the MEG experiments, and the conditions tested in follow-up experiments will depend on the results obtained with these conditions plus results obtained in both behavioral and ERP pilot work, and the results obtained in WP2.1. The conditions to be tested in the first set of experiments in WP3 are either conditions known to produce robust behavioral effects, or are straightforward extensions of the FLLD paradigm for investigating repetition and semantic flanker effects. These will include orthographic flanker effects: RO ROCK CK vs. CK ROCK RO vs. PA ROCK ST; repetition flanker effects: ROCK ROCK ROCK vs. TREE ROCK TREE vs. #### ROCK ####; and semantic flanker effects: KNIFE FORK KNIFE vs. TABLE FORK TABLE. The semantic categorization task (living vs. non-living) will also be used in these experiments.

3.1 FLLD and ERP recordings
Specific aims: Plot the time-course of spatial integration of orthographic information as it occurs in the FLLD paradigm, and establish ERP signatures for the different components of the overall process of spatial integration of orthographic information. Compare the ERP signatures of spatial integration with those obtained from prior research concerning temporal integration (Grainger & Holcomb, 2009) in order to better specify the information processing involved.

My prior research in collaboration with P. Holcomb combined the masked priming paradigm and ERP recordings in order to describe the time-course of component processes in single word reading (for a review see Grainger & Holcomb, 2009). In particular, this past research has built on the sensitivity of on-going word recognition processes, as revealed in the ERP waveform, to the integration over time of information extracted from temporally distinct stimuli (prime and target) presented at the same location. Here I propose to exploit a similar sensitivity to integration of information extracted from spatially distinct but temporally overlapping stimuli. The proposed flanking letter ERP experiments will be used to better specify the nature of the effects seen in prior behavioral research by providing key information with respect to the timing of the effects. Our prior ERP work with the masked priming paradigm points to the N250 component (peaking at 250 ms post-target onset) as the earliest component to be sensitive to orthographic flanking effects. I therefore expect to observe a modulation of the N250 as a function of orthographic overlap of flanking letters and central target words. These effects should be independent of flanker lexicality, while effects seen on the later N400 component should, on the other hand, be sensitive to flanker lexicality and the semantic relatedness of targets and flankers. Flanking letter effects seen prior to the N250 are expected to reflect purely visual integration processes and are therefore expected to occur independently of orthographic overlap (i.e., driven by the simple presence of flanking stimuli vs. absence of flankers).

3.2 FLLD and MEG recordings
Specific aim: Locate the neural structures involved in the spatial integration of orthographic information, and further specify the timing of such processes.

Within the theoretical framework proposed by Grainger et al. (2016) and its specific implementation in the POP-R model one can generate predictions with respect to which brain regions are likely to be involved in the different component processes, and when such processing should arise. Here I propose to use MEG in combination with the FLLD paradigm in order to put such predictions to test. The predictions are straightforward: prior to spatial integration, visual features are mapped in parallel onto gaze-centered letter identities in retinotopic visual areas. Following this, sublexical integration of orthographic information spanning several words is performed by neural structures in left ventral occipito-temporal cortex and this information feeds higher-level language processing in temporal and frontal regions. In order to examine this I propose to test the same set of flanker conditions as tested in WP3.1 (orthographic, repetition, semantic) in both lexical decision and semantic categorization tasks while recording MEG responses. Another series of experiments will compare letter and non-letter stimuli using the same-different matching task (WP 2.2). The goal here is to isolate letter-specific processing in retinotopic visual areas, following-up on prior evidence obtained using fMRI (Chang et al., 2015).

WP4. Word-in-phrase identification experiments
Collaborators: Dr. J.M Badier (Aix-Marseille University), Dr. S. Dufau (Aix-Marseille University), PostDocs-1&2
Major goal: Use the novel RPVP paradigm with an aim to provide a new window on word identification processes operating in parallel across multiple words.

Results obtained with the first known implementation of the RPVP paradigm (Asano & Yokosawa, 2011) were instrumental in motivating the multi-channel approach to word identification during reading adopted in the POP-R model. Given the dearth of research using this paradigm, here I propose to exploit this technique as a new window on parallel word identification processes.

4.1 Behavioral RPVP experiments
Specific aim: To provide further evidence in favor of word identification processes operating in parallel across multiple words written in an alphabetic script.

The results of Asano and Yokosawa (2011) in Japanese Kanji (a logographic script) suggest no role for syntactic constraints in determining the activity of word identities activated in parallel. Results obtained in our lab using the FLLD paradigm, on the other hand, have revealed a strong influence of syntactic congruency across target and flankers. I therefore propose to compare post-cued word-in-phrase identification in syntactically correct phrases against performance with scrambled lists of the same words. Contrary to the results of Asano and Yokoswa (2011), the POP-R model predicts a sentence superiority effect operating on top of effects of between-word semantic relatedness, and pilot work in our lab suggests that there is indeed a purely syntactic sentence superiority effect. This pilot work found superior identification of the target word (e.g., BOY) in syntactically correct sentences (e.g., THE BOY CAN EAT) compared with scrambled lists of words (e.g., CAN BOY THE EAT), and independently of the position of the target in the list of words. This preliminary study will be followed-up by a more systematic investigation of syntactic and semantic influences on word-in-phrase identification, testing the following conditions with examples given for the target word KNIFE at position 2: Syntax + semantics: THE KNIFE AND FORK; Syntax only: THE KNIFE WAS COLD; Semantics only: AND KNIFE FORK THE; Unrelated: AND KNIFE COLD THE. Experiments will also be run in order to disentangle local syntactic contingencies from more global syntactic influences. Thus, for example, the target word CAT will be tested in three different conditions: THE CAT WAS ILL; THE CAT ILL WAS; WAS CAT THE ILL. Another series of experiments will examine the influence of orthographic overlap across words on performance in the RPVP paradigm. The POP-R model predicts that orthographic overlap across neighboring words should facilitate word identification via the boost in sublexical orthographic activation. Thus identification of the target word CAT should be better in THE FAT CAT SAT DOWN than in THE OLD CAT RAN AWAY. It is important to note that such parallel facilitation, if observed, will contrast sharply with the type of sequential inhibition observed with the RSVP (rapid serial visual presentation) paradigm, and referred to as "orthographic repetition blindness" whereby identification of CAT is hampered following FAT compared with when it follows OLD (Harris & Morris, 2000). Finally, I propose to test the effect of mask type (continuous vs. discontinuous) on performance in the RPVP paradigm. The prediction here is that discontinuous masks aligned with the word stimuli (as shown in Figure 4) facilitate the maintenance of a short-term spatiotopic representation of word identities, and a continuous mask should disrupt this, leading to a drop in performance in the RPVP paradigm.

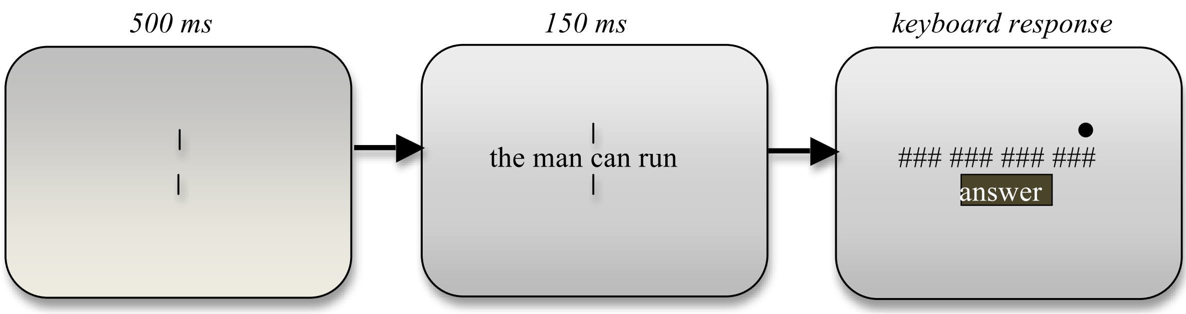

Figure 4. The RPVP (Rapid Parallel Visual Presentation) paradigm. Participants are shown short sequences of words simultaneously for 150 ms followed by a post-mask and cue for identifying the word that was presented at the cued location.

4.2 RPVP experiments with ERP and MEG recordings

Specific aims: Investigate the electrophysiological correlates of the sentence superiority effect and compare these with ERP components known to be related to sentence-level processing. Situate the neural underpinnings of the sentence superiority effect with respect to current knowledge of the neural structures involved in syntactic and semantic processing of sentences.

Here I plan to build on the results obtained in WP4.1, exploiting the conditions generating the largest behavioral effects, and testing these conditions with ERP and MEG recordings. WP4.2 complements WP2, where ERP and MEG recordings were combined with the FLLD paradigm. While WP2 provides information with respect to the early phases of spatial integration processes, WP4.2 will provide information with respect to the neural processing involved in parallel word identification and subsequent semantic and syntactic analyses. Modulation of the N250 (orthographic), P325 (lexical), N400 (semantic)[7] and P600 (syntactic) components in the RPVP paradigm will provide key information with respect to the factors contributing to performance in word-in-phrase identification. The combined ERP and MEG experiments will provide crucial information with respect to the timing of retinotopic, spatiotopic, and location-invariant encoding of orthographic information during reading, the key ingredients of the POP-R model.

WP5. Sentence reading experiments with combined eye movement and ERP recordings
Collaborators: Dr. S. Dufau (Aix-Marseille University), Prof. P. Holcomb (San Diego State University), PostDoc-3
Major goal: Test specific predictions derived from the POP-R model with respect to orthographic processing during sentence reading.

Here I propose to exploit the full potential of eye movement recordings during sentence reading and to test predictions of the POP-R model than cannot be tested with the simpler FLLD or RPVP paradigms. The combination of ERP recordings with eye-movement recordings will enable the measurement of fixation-related potentials (FRPs: Hutzler et al., 2007; Dimigen et al., 2012) and fixation-onset related EEG activity (FOREA: Weiss, Knakker, & Vidnyansky, 2016). This will provide important additional information with respect to how the spatial integration of orthographic information affects reading. Weiss et al. (2016) have recently shown that a manipulation of inter-letter spacing in sentence reading affects FOREA in two early time-windows (120-175ms; 230-265ms) that align almost perfectly with the N/P150 and N250 ERP components identified in our prior work on single word reading (Grainger & Holcomb, 2009). In WP5 I propose to use ERP recordings during sentence reading in order to provide additional leverage with respect to understanding the mechanisms driving spatial integration of orthographic information during sentence reading.

5.1 Physical manipulations of text during reading
Specific aim: Test predictions derived from the POP-R model concerning how physical changes in text affect orthographic processing during reading.

In these experiments, participants will silently read sentences for meaning, and the sentences will be physically modified during an eye-movement with no change to their orthographic content. The physical manipulations will include changes in inter-letter spacing (including an un-spaced text condition) and small shifts in horizontal sentence location. One key prediction of the POP-R model is that reading text without spaces is essentially reading with a single channel. In these conditions, spatiotopic word representations can no longer be formed, and the ordering of word identities for sentence comprehension is achieved uniquely on the basis of timing of word identification. One means to test this prediction is to repeat our prior work on orthographic parafoveal-on-foveal effects in sentence reading using the boundary technique, and with high frequency orthographic neighbors as parafoveal stimuli (Snell, Vitu, & Grainger, 2016). In this prior work, the lexical status of orthographically related parafoveal stimuli did not have an influence, and both related word and nonword parafoveal stimuli caused reduced fixation durations on the foveal word. Here I predict that with unspaced text, parafoveal word neighbors should inhibit processing of the foveal word, mimicking the pattern seen in the masked priming paradigm (Davis & Lupker, 2006; Segui & Grainger, 1990). Another prediction of the POP-R model is that small shifts in horizontal sentence location (i.e., one letter space to the left or to the right), operated during an eye movement, should disrupt the retinotopic-spatiotopic remapping that is essential for keeping track of which part of the sentence stimulus (i.e., which "blob") is associated with which word identity. Again, this manipulation should force the reading network to revert to a single-channel process.

[7] See Barber, van der Meij, and Kutas (2013) and Zhang, Li, Wang, and Wang (2015) for semantic N400 effects in a sequential flanking-words paradigm providing evidence in favor of parallel semantic processing of words.

5.2 Orthographic parafoveal-on-foveal ERP effects
Specific aim: Use ERPs in order to examine the time-course of orthographic parafoveal-on-foveal effects during sentence reading.

Here I propose to examine orthographic parafoveal-on-foveal effects using the boundary technique (Rayner, 1975; see page 2 for a description of this technique) while recording ERPs. The use of ERPs will provide valuable information with respect to the precise timing of such parafoveal-on-foveal influences. A first series of experiments will examine parafoveal-on-foveal repetition effects, orthographic effects, and semantic effects. Another series of experiments will test the impact of changing the relative visibility of foveal / parafoveal stimuli in an attempt to modify the size of parafoveal-on-foveal influences. Reducing foveal visibility should increase processing time on the foveal word hence increasing the impact of the parafoveal stimulus, and particularly when its visibility is increased. Visibility will be manipulated by a change in contrast, or more specifically, a change in stimulus luminance for a constant background luminance (see Marx, Hawelka, Schuster, & Hutzler, 2015, for a similar manipulation of the saliency of parafoveal previews). Prior research has shown that depriving readers of parafoveal information, by masking or removing word N+1 when fixating word N, disrupts reading (Rayner, Liversedge, & White, 2006). Here the prediction is that a similar handicap can be caused by increasing the potential interference of parafoveal stimuli during foveal word processing. It is also possible that the optimal conditions for generating parafoveal preview benefits while reducing parafoveal-on-foveal interference are not the equiluminant conditions of normal text.

WP6. Spatial integration of orthographic information in developing readers
Collaborators: Dr. S. Ducrot (Aix-Marseille University), Prof. B. Lété (Université Lyon 2), PhD-2, PostDoc-3
Major goal: Describe the developmental trajectory of spatial integration of orthographic information that is associated with normal reading development and examine its relation to the development of other linguistic and non-linguistic capacities.

Knowledge of the development of single word reading abilities has grown considerably in the last decade, with an increasing number of studies applying paradigms that had typically been reserved for studies with adults. The same holds for studies of sentence reading in children using eye-movement recordings (e.g., Schroeder, Hyönä, & Liversedge, 2015). Here I propose to once again exploit the simplicity of the FLLD paradigm, this time for cross-sectional and longitudinal investigations of orthographic processing in primary school children. A subset of the cross-sectional experiments will use eye movement recordings during sentence reading with children tested at the lab rather than at school.

Prior ERC funding enabled the running of several large-scale cross-sectional studies of the development of orthographic processing in single word reading (Grainger et al., 2012; Ziegler et al., 2014; Grainger, Bertrand, et al., 2016) and the elaboration of a novel account of orthographic development (Grainger & Ziegler, 2011; Grainger et al., 2012). Here I propose to extend this research in two main directions: Firstly, in line with the proposed adult studies, to investigate processing of orthographic information spanning multiple words and how this impacts on sentence reading during reading development; and secondly to relate the development of orthographic processing abilities to changes in other linguistic and non-linguistic capacities. To this end, all children will be tested for reading and spelling ability, vocabulary size, visual span, and working memory span (including visual short-term memory). A first series of FLLD experiments will use a cross-sectional design, testing children in grades 1-5 of primary education at the school premises. These FLLD experiments will test for orthographic, repetition, and semantic flanker effects. A second series of experiments using a cross-sectional design will test children at the laboratory in a sentence-reading paradigm with eye-movement recordings and the boundary technique. Here the aim is to plot the developmental trajectory of orthographic parafoveal-on-foveal effects during sentence reading. Finally, the FLLD cross-sectional experiments will be complemented with an ambitious 4-year longitudinal study (grades 2 to

5), involving a large sample of children (approximately 100 children tested across multiple schools in the Marseille region and 100 children tested in multiple schools in Lyon). The large number of children is necessary for the analysis of individual differences, and in order to compensate for inevitable dropout.

Apart from providing valuable knowledge concerning the development of orthographic processing, this research will provide insights with respect to a possible link between difficulties in learning to read and processes linked to the spatial integration of orthographic information. Indeed, it has been hypothesized that some dyslexic children might be abnormally sensitive to information in peripheral vision (Geiger & Lettvin, 1987). Related to this is the growing consensus that a significant number of dyslexic children suffer from a purely visuo-attentional deficit (Facoetti et al., 2011) possibly in addition to, or even the cause of rather the consequence of, their overall difficulty in reading (Boros et al., 2016). The present developmental research is expected to provide important insights with respect to a possible role for excessive spatial integration of orthographic information as a handicap toward fluent reading.

Section c. Resources (including project costs)

Dedicating 80% of my time to the project I will play a leading role in its overall management, in the design of the experiments to be performed, and the presentation and writing-up of results. Each work package involves different senior collaborators chosen for their expertise related to the work to be performed. **M. Meeter** (VU Amsterdam), an expert in computational modeling, is the key collaborator for the implementation of the POP-R model. **J.M. Badier** (Institute de Neurosciences des Systèmes, Marseille) is in charge of the local MEG facilities and his collaboration is essential for the success of the planned MEG experiments. **S. Dufau** (Laboratoire de Psychologie Cognitive, Marseille) has considerable expertise in EEG research and will also play a key role in the combined EEG and eye-movement research. **P. Holcomb** (SDSU, San Diego) has been my major collaborator on all EEG-related research over the last 15 years. **S. Ducrot** (Laboratoire Parole et Langage, Aix-en-Provence) and **B. Lété** (Lyon University) are currently two major collaborators on developmental reading research and will play a key role in setting-up and supervising these experiments in schools in Marseille and Lyon.

As described in the different work packages (WPs 1-6), the project requires the contribution of 2 PhD students (2 X 3 years) for a total cost of 209 816 € and 3 post-docs (3 X 5 years) for a total cost of 1 083 267 €. The PhD students and post-docs will work under the joint supervision of the PI and the specific senior collaborators involved in the different work packages. Travel expenses are requested for the PI, post-docs, and PhD students to regularly attend international conferences (e.g., Psychonomic Society, ESCoP) in order to present obtained results, and for travel costs for the collaboration with M. Meeter (Amsterdam), for an estimated total of 50 000 €. Subcontracting costs are requested to pay for use of the MEG facilities and to pay for participants in the MEG and EEG studies for a total cost of 50 000 €.

Resources available outside of the requested budget: The project involves the use of combined eye-tracking and EEG recordings that requires a dedicated set-up. The estimated cost for this is 100 000 € which will be funded on our own resources, as will be costs of laptop and desktop computers. Experiments requiring separate use of either EEG recordings or eye-movement recordings will be performed using existing equipment.

Cost Category			Total in euro
Direct Costs	**Personnel**	PI	585 705
		Senior Staff	-
		Postdocs	1 083 267
		Students	209 816
		Other	-
	i. Total Direct costs for Personnel (in euro)		1 878 788
	Travel		50 000
	Equipment		-
	Other goods and services	Consumables	-
		Publications (including Open Access fees), etc.	30 000
		Other (please specify)	-
	ii. Total Other Direct Costs (in euro)		80 000
A – Total Direct Costs (i + ii) (in euro)			1 958 788
B – Indirect Costs (overheads) 25% of Direct Costs (in euro)			489 697
C1 – Subcontracting Costs (no overheads) (in euro)			50 000
C2 – Other Direct Costs with no overheads (in euro)			-
Total Estimated Eligible Costs (A + B + C) (in euro)			**2 498 485**
Total Requested Grant (in euro)			**2 498 485**

Duration of the project in months:	**60**
Percentage of working time the PI dedicates to the project over the period of the grant:	**80%**
Percentage of working time the PI spends in an EU Member State or Associated Country over the period of the grant:	**95%**

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