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Camille L Grasso, Johannes C Ziegler, Jennifer T Coull, Marie Montant

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1 Space-time congruency effects using eye movements during  
2 processing of past-and future related words

3 Camille L. Grasso<sup>1</sup>, Johannes C. Ziegler<sup>1</sup>, Jennifer T. Coull<sup>2</sup>, & Marie Montant<sup>1</sup>

4 <sup>1</sup>Aix-Marseille Université, CNRS, Laboratoire de Psychologie Cognitive (UMR 7290)

5 <sup>2</sup>Aix-Marseille Université, CNRS, Laboratoire de Neurosciences Cognitive (UMR 7291)

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18 **Author Note**

19 Camille L. Grasso  <https://orcid.org/0000-0002-7549-7395>

20 Email: [grassocamille@gmail.com](mailto:grassocamille@gmail.com)

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23

24 **Abstract**

25

26 In Western cultures where people read and write from left-to-right, time is represented along  
27 a spatial continuum that goes from left to right (past to future), known as the mental timeline  
28 (MTL). In language, this MTL was supported by space-time congruency effects: people are  
29 faster to make lexical decisions to words conveying past or future information when  
30 left/right manual responses are compatible with the MTL. Alternatively, in cultures where  
31 people read from right-to-left, space-time congruency effects go in the opposite direction.  
32 Such cross-cultural differences suggest that repeated writing and reading dynamic  
33 movements are critically involved in the spatial representation of time. In most experiments  
34 on the space-time congruency effect, participants use their hand for responding, an effector  
35 that is associated to the directionality of writing. To investigate the role of the directionality  
36 of reading in the space-time congruency effect, we asked participants to make lateralized eye  
37 movements (left or right saccades) to indicate whether stimuli were real words or not (lexical  
38 decision). Eye movement responses were slower and higher in amplitude for responses  
39 incompatible with the direction of the MTL. These results reinforce the claim that repeated  
40 directional reading and writing movements promote the embodiment of time-related words.

41

42 **Key words:** Abstract concepts, lexical decision, embodiment, eye-tracking, space, time.

43

## 44 **Introduction**

45

46 Time is not associated with any tangible temporal stimulus, there are no sensory  
47 receptors for time, and no dedicated "time area" in the brain. So how can embodied theories  
48 represent words that refer to time? One possibility is that time-related words are spatially  
49 represented and ordered along linear axes known as mental timelines (MTL; Bender & Beller,  
50 2014; Bonato et al., 2012; Cooperrider & Núñez, 2009). Empirical evidence for MTL comes  
51 from experiments that manipulated the congruency between the temporal content of verbal  
52 stimuli and the spatial location of required responses, resulting in a space-time congruency  
53 effect (Eikmeier et al., 2015; Kong & You, 2012; Maienborn et al., 2015; Santiago et al., 2007;  
54 Torralbo et al., 2006). On the lateral axis, space-time congruency effects correspond to faster  
55 left responses for past-tense stimuli (e.g., *I listened*) and faster right responses for future-  
56 tense stimuli (e.g., *I will listen*). These effects are typically observed when participants make  
57 explicit temporal judgments (Aguirre & Santiago, 2017; Casasanto & Bottini, 2014; Kong &  
58 You, 2012), but reduced when participants make *non*-temporal judgments, such as lexical  
59 decisions (e.g., Maienborn et al., 2015; see von Sobbe et al., 2019 for a meta-analysis).  
60 Therefore, it has been suggested that the processing of time-related words does not  
61 automatically engage spatial networks underlying the MTL (Maienborn et al., 2015;  
62 von Sobbe et al., 2019). However, Grasso et al. (2021) found space-time congruency effects  
63 even when temporal processing was implicit (lexical decisions about past/future-conjugated  
64 verbs and pseudoverbs) as long as the task involved directional hand movements rather than  
65 simple key presses (see also Scheifele et al., 2018; Sell & Kaschak, 2011). These results suggest  
66 that spatially directed movement (and therefore the motor system) could play a critical role  
67 for the emergence of space-time congruency effects. Interestingly, the congruency effect was  
68 only observed for real, not pseudo, verbs, reinforcing the hypothesis that the motor system  
69 contributes to the lexical processing of past and future related words.

70           If the motor system is a key component for the representation and processing of  
71 abstract temporal concepts, what kind of sensorimotor experience might link space and time  
72 into a left-to-right MTL? Interestingly, it has been shown that the MTL goes from left-to-right  
73 in cultures with a left-to-right writing system, whereas the reverse pattern is observed in  
74 cultures with a right-to-left writing system (Ouellet et al., 2010), which suggests that the  
75 lateral MTL results from extensive reading and writing experience (Fuhrman & Boroditsky,  
76 2010).

77           As concerns language, one prediction is that if the spatial representation of the  
78 temporal content of words comes from repeated spatially directed movement executed  
79 during reading and writing, then space-time congruency effects in implicit temporal tasks  
80 should not be limited to hand movements (used for writing) but should also be observed for  
81 eye movements (used for reading). To test this hypothesis, the present study investigated  
82 whether space-time congruency effects could also occur when participants gave non-  
83 temporal decisions about past/future words using lateral saccades. French verbs and pseudo  
84 verbs were presented on a screen in conjugated form (i.e., past or future), and participants  
85 had to decide as quickly as possible whether the verb was real or not by producing a saccade  
86 towards the left or the right side of the screen. Experimental design and stimuli were taken  
87 from Grasso et al. (2021). The grammatical verbal system in French makes it possible to use  
88 the same word stem combined with a suffix that indicates either past tense (je marchais [I  
89 walked]; je rêvais [I dreamt]) or future tense (je marcherai [I will walk]; je rêverai; [I will  
90 dream]). Having the same word stem for different temporal conditions nicely controls for  
91 possible orthographic, lexical, and semantic confounds.

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96 **Materials and Methods**

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98 *Participants*

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100 The study involved 64 participants from Aix-Marseille University (France). Nine participants  
101 were excluded from analyses due to high errors rates or technical data acquisition issues.  
102 The remaining 58 participants (48 women, 54 right-handed, aged 18-42 years,  $M = 22.2$ ;  $SD$   
103  $= 4.6$ ) were French native speakers, reported normal or corrected-to-normal vision and no  
104 neurological or psychiatric disorder. Participants gave informed consent prior to  
105 participation and were informed that data were collected anonymously. The study was  
106 approved by the Institutional Review Board of Aix-Marseille University.

107

108 *Design and Stimuli*

109

110 Because the main objective of this study was to determine whether previous results  
111 obtained with hand movements (Grasso et al., 2021) could be generalised to eye movements,  
112 we used the same design as Experiment 1 of Grasso et al. (2021). This experiment (which  
113 included the temporal priming words “yesterday” or “tomorrow”) had the strongest effect  
114 size (Cohen’s  $d = .74$ ) and control experiments confirmed that the presence or absence of  
115 primes did not interact with the congruency effect. Stimuli were taken from Grasso et al.  
116 (2021) and consisted of 80 French word stimuli (verbs) and 80 pseudoword stimuli  
117 (*pseudoverbs*, see Appendix in Grasso et al., 2021). Each word or pseudoword was presented  
118 in past- or future-tense (e.g., je laissais/je laisserai ; je gontrais/je gonttrerais, for words and  
119 pseudowords respectively) at the centre of the screen (Figure 1). To ensure that participants  
120 saw each word or pseudoword only once, we created four counterbalanced lists of 160  
121 stimuli (80 words, 80 pseudowords) using a Latin-Square design. Half of the stimuli in each

122 list were in the past tense, half were in the future tense. All stimuli were preceded by the  
123 pronoun *je* (“I”).

#### 124 *Apparatus*

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126 Eye movements were recorded with an EyeLink 1000 system (SR Research,  
127 Mississauga, ON, Canada) with high spatial resolution (0.01°) and a sampling rate of 1000 Hz.  
128 Viewing was binocular, but only the right eye was monitored. Stimuli were displayed on a  
129 20-inch ViewSonic CRT monitor with a refresh rate of 85Hz and a screen resolution of 1024  
130 x 768 pixels (30 x 40 cm). Stimuli were presented in black 37-point monospaced fonts (droid  
131 sans mono) on a grey background. The experiment was created using OpenSesame (Mathôt  
132 et al., 2012). Participants were instructed to give Yes (“it’s a word”) or No (“it’s not a word”)  
133 responses in a lexical decision task by moving their eyes towards the left or right of the  
134 screen. Left and right correct response areas were spatially delimited by two virtual  
135 boundaries at +/-600 pixels from the screen’s centre. Participants were seated 86 cm from  
136 the monitor, such that every 3 characters equalled approximately 1° of visual angle. We used  
137 a chin-rest to minimize head movements.

138

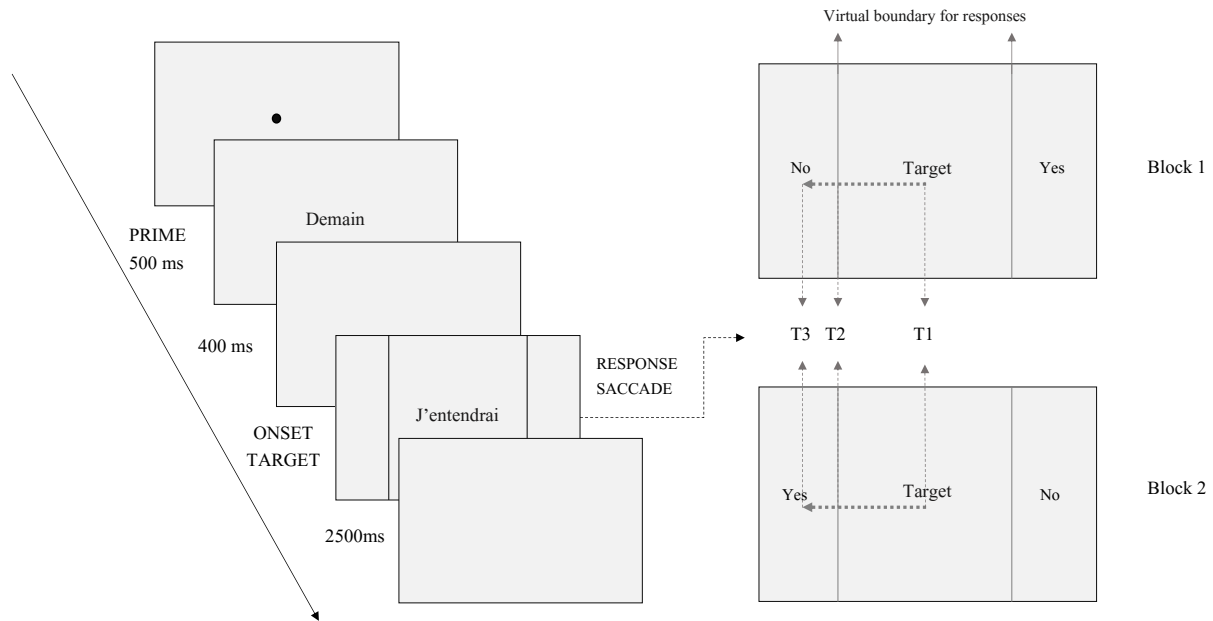
#### 139 *Procedure*

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141 The experiment was run in a quiet testing room. Participants were instructed to  
142 decide as rapidly and as accurately as possible whether the stimulus was a real French word  
143 or not (i.e., a lexical decision) by moving their eyes towards the left / right side of the screen.  
144 Half of the participants started with “yes” responses towards the left (yes-left) and half with  
145 “yes” responses towards the right (yes-right), and all participants switched response sides  
146 halfway through the experiment. Participants completed a short training session of 20 trials  
147 before each experimental block. Each participant saw a total of 80 words and 80  
148 pseudowords in a pseudo-randomized order across two counterbalanced blocks (yes-right

149 or yes-left). For the yes-right block, future-tense words were congruent with the MTL and  
150 past-tense words were incongruent (see Figure 1). In each block, there were 40 words and 40  
151 pseudowords, half of each being conjugated in the past tense and half in the future. In the  
152 yes-left block, past-tense words were congruent and future-tense words were incongruent.  
153 At the beginning of the experiment, eye position was calibrated using a 9-point calibration  
154 grid. The experiment started once the training session was completed. Each trial started with  
155 a drift correction dot presented at the centre of the screen. Participants were instructed to  
156 fixate this dot, which triggered the onset of a prime stimulus: *hier* or *demain* (“yesterday” or  
157 “tomorrow”) displayed for 500ms, followed by a 400ms blank screen and then finally by the  
158 stimulus (i.e., a word or pseudoword). The stimulus remained on the screen until the  
159 participants responded by making a saccade. Saccades that crossed the virtual left or right  
160 boundaries were considered as responses, whereas saccades that did not cross the  
161 boundaries were considered as refixations or microsaccades (depending on their  
162 amplitude). Saccade response side was automatically registered when the eyes crossed the  
163 left or right boundary. Responses time corresponded to saccade latency (latency between  
164 the onset of the stimulus and onset of the saccade). To assess the kinematic features of the  
165 saccade, we measured saccade amplitude expressed in degrees of visual angle. After each  
166 response, participants were instructed to fixate the central black dot in order to start the next  
167 trial. The time interval between the onset of the stimulus and the new fixation dot was  
168 2500ms. A break was offered to participants every 20 trials. Half-way through the experiment  
169 (80 trials) participants were instructed to switch sides for yes/no responses. Each testing  
170 session lasted approximately 1 hour.





171

172 **Figure 1.** Task design. Once participants fixated the central dot, a prime (*hier* or *demain*, i.e.,  
 173 “yesterday” or “tomorrow”) was displayed, followed by a word or pseudoword (e.g.,  
 174 *j’entendrai* as a future tense verb or *j’entendais* as a past tense verb). Participants made their  
 175 lexical decision by moving their eyes towards the left or right side of the screen (delimited by  
 176 two virtual boundaries). In this example, the yes-response for the word conjugated in the  
 177 future tense is congruent with the MTL in Block 1 (rightward eye movement) but  
 178 incongruent in Block 2 (leftward eye movement). Saccadic responses were automatically  
 179 detected and recorded as soon as the eyes crossed the left or right virtual boundaries on the  
 180 screen. We recorded the initiation time (response time) and the amplitude (in degree of  
 181 visual angle) of the saccades. T1 corresponds to the onset-time of the saccade, T2  
 182 corresponds to the boundary-crossing time, and T3 corresponds to the landing time.  
 183 Therefore, response latencies correspond to the response initiation time, which is the delay  
 184 between the onset of the stimulus and onset of the saccade response (T1). Saccades that did  
 185 not reach the left/right boundaries were automatically discarded from the analyses.  
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196 **Data analyses**

197

198           We recorded and analyzed saccade latency (in milliseconds), and saccade amplitude  
199 (in degrees of visual angle). Saccadic eye movements are stereotyped ballistic movements  
200 that cannot be modified once initiated (Gilchrist, 2011), and can be described by their  
201 latency and their angular rotation (Findlay & Gilchrist, 2001, 2003). Saccade latency  
202 corresponds to the time needed to process the visual stimulus, to make a decision, and to  
203 program the motor response (Gilchrist, 2011). Saccade amplitude corresponds to the spatial  
204 distance between starting and landing positions of the eyes. Although this feature of the  
205 saccade may appear to be stereotyped (Edelman et al., 2007), it has been shown that  
206 linguistic factors (e.g., unusual orthographic patterns) influence saccade amplitude  
207 (Beauvillain et al., 1996). Given that the accuracy of goal-directed movements, including  
208 saccades, “depends on the quality of the encoding of spatial information by the central  
209 nervous system and the frame of reference” (Ghafouri & Lestienne, 2006, p.25), we predicted  
210 that saccade programming as measured by saccade amplitude should be sensitive to the  
211 space-time congruency effect. Obtaining such an effect would imply that motor planning  
212 networks are involved in the representation of words referring to time.

213           Both saccade latency and amplitude were analyzed using linear Mixed Effect Models  
214 (LMEs) with participants and items as crossed random effects (Baayen, 2008; Barr, 2013).  
215 Note that the space-time congruency effect is indexed by the interaction between response  
216 side and verb tense. That is, when the side of response for a past-tense word switches from  
217 left to right from one block to the other, the word stops being congruent and, instead,  
218 becomes incongruent. Similarly, when the side of the response for a future-tense word  
219 switches from left to right, the word stops being incongruent and becomes congruent (see  
220 Figure 1). Data were fitted with lmer functions from the lme4 package (Bates et al., 2015) in  
221 the R statistical computing environment (Version 3.5.2; R Core Team, 2020). We report

222 unstandardized regression coefficients, standard errors (SEs), and t values. Fixed effects  
223 were deemed reliable if  $|t|$  was greater than 1.96 (Baayen, 2008). In a forward stepwise model  
224 selection procedure, fixed and random effects of the models were selected according to the  
225 Akaike Information Criterion (AIC; Akaike, 1973), the Bayesian Information Criterion (BIC;  
226 Schwarz, 1978) using the `anova()` function of the package `lmerTest` package (Kuznetsova et  
227 al., 2017) for model comparison. Therefore, fixed effects and random slopes were only  
228 included if they significantly improved the model parsimony (as assessed by the AIC/BIC).  
229 We built our models using the following procedure: we started with an empty model  
230 containing no fixed effect but a random intercept for participant and a random intercept for  
231 item. In a second step, fixed effects were selected using the forward stepwise selection  
232 procedure. Finally, we included a random slope for each of the selected fixed effects if it  
233 improved the model parsimony (as assessed by the AIC/BIC). Model assumptions were  
234 checked for each model using the `check_model()` function from the `performance` (Lüdtke  
235 et al., 2021) package. Following the procedure described by Brysbaert and Stevens (2018), we  
236 conducted power analysis based on 200 simulations with `powerSim` functions from the `simR`  
237 package (Green & MacLeod, 2016). We used the Satterthwaite method as implemented by the  
238 `afex` package (Singmann et al., 2021) for computing p-values. To create figures, we used the  
239 `emmeans` package (Lenth, 2021) and computed estimated marginal means (EMMs) for the  
240 interaction between response side and verb tense for each model (see Figure 2).

241

## 242 **Results**

243

244 Saccade latency and saccade amplitude were analysed for the 58 participants. We  
245 removed trials containing blinks (2.91%), trials with no-response (2.21%), trials with negative  
246 fixation duration (2.41%), trials with a total fixation duration below 100ms (anticipatory  
247 responses, 1.63%), and trials in which the initial position of the response saccade on the x-

248 axis was outside the left-or-right boundaries (0.72%)<sup>1</sup>. Trials with latencies greater than the  
249 possible trial duration (i.e., above 2500ms) or less than 300ms (0.06%), and trials with  
250 saccade amplitude greater than 30 degrees and less than 2 degrees (0.20%) were also  
251 discarded. Finally, after removing incorrect response trials (3.91%) latency outliers were  
252 removed following the classic  $\pm 2.5$  standard deviations from the participants' mean  
253 response time (2.66%). Statistical analyses were conducted separately for words and  
254 pseudowords.

255

### 256 *Words*

257

258 For the analysis of saccade latencies, the final model included Time (past vs future),  
259 Side (left vs right) and their interaction as fixed effects, as well as word length (in pixels) and  
260 number of word refixations (i.e., the number of fixations that were made on the word before  
261 providing the response) as covariates. The model also included by-participant and by-item  
262 random intercepts, and a random slope for Time, Side and number of refixations by-  
263 participants and a random slope for time by-items.

264 Overall, participants were significantly faster to initiate a response saccade to the  
265 right side of the screen than to the left side ( $b = 20.63$ ,  $SE = 10.14$ ,  $t = 2.03$ ,  $p = .044$ ) but there  
266 was no significant difference for past versus future tense words ( $b = 11.86$ ,  $SE = 8.62$ ,  $t = 1.37$ ,  
267  $p = .171$ ). Saccade latencies increased significantly with word length ( $b = 1.10$ ,  $SE = 0.27$ ,  $t =$   
268  $4.30$ ,  $p < .0001$ ) and number of refixations ( $b = 84.97$ ,  $SE = 5.83$ ,  $t = 14.57$ ,  $p < .0001$ ).  
269 Importantly, the congruency effect, which is the interaction between Time and Side, was  
270 highly significant ( $b = -26.49$ ,  $SE = 9.90$ ,  $t = 2.68$ ,  $p = .007$ ). That is, saccade latencies to past-  
271 tense stimuli were slower when the correct (“yes”) response was on the right rather than the

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<sup>1</sup> A saccade response was detected as soon as the eyes crossed the virtual left and right boundaries on the screen. Thus, if the initial position of the eye on the x-axis at the beginning of a trial is not at the center of the screen but outside these boundaries, the trial is considered impossible and discarded.

272 left, and saccade latencies for future-tense verbs were slower when the correct response was  
273 on the left versus the right (see Figure 2). The power of this model (i.e., congruency and time)  
274 in 200 simulated studies was .81,  $CI_{95} = [74, 86]$ . No other effect or interaction was significant.

275 The final model for the analysis of saccade amplitude included Time, Side and their  
276 interaction as fixed effects, as well as number of refixations as a covariate. The model also  
277 included by-participant and by-item random intercepts, and a random slope for Side by-  
278 participant. Results showed a marginal effect of the number of word refixations ( $b = -0.05$ ,  $SE$   
279  $= 0.02$ ,  $t = 1.89$ ,  $p = .060$ ). More importantly, the interaction between Time and Side was  
280 significant ( $b = -0.20$ ,  $SE = 0.08$ ,  $t = 2.28$ ,  $p = .023$ ) reflecting the space-time congruency effect  
281 (see Figure 2). The power of this model (i.e., congruency and time) in 1000 simulated studies  
282 was .66,  $CI_{95} = [59, 73]$ . No other effect or interaction was significant.

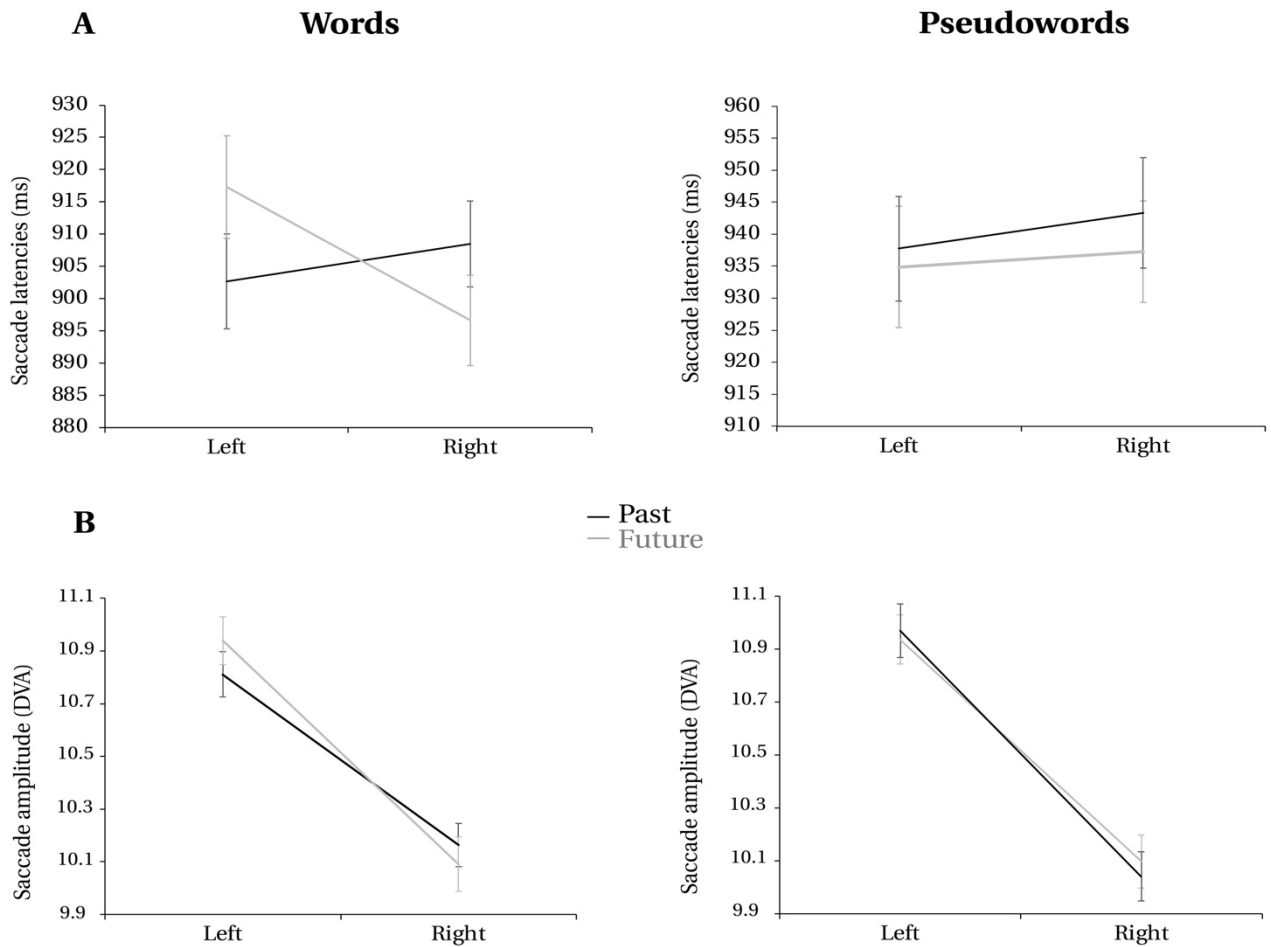
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#### 284 *Pseudowords*

285

286 The final model for the analysis of saccade latencies to pseudowords was exactly the  
287 same as that for saccade latencies to words. Saccade latencies increased significantly as a  
288 function of pseudoword length ( $b = 0.81$ ,  $SE = 0.26$ ,  $t = 3.19$ ,  $p = .002$ ) and the number of  
289 refixations ( $b = 83.60$ ,  $SE = 5.41$ ,  $t = 15.45$ ,  $p < .001$ ). The interaction between Time and Side  
290 was not significant ( $b = 3.17$ ,  $SE = 9.74$ ,  $t = 0.33$ ,  $p = .744$ ) No other effect or interaction was  
291 significant.

292 The final model for the analysis of saccade amplitude included Time, Side, number  
293 of pseudoword refixations and their interaction as fixed effects, and by-participant and by-  
294 item random intercepts. Results showed a significant effect of Side ( $b = 0.00$ ,  $SE = 0.00$ ,  $t =$   
295  $3.05$ ,  $p = .002$ ), number of pseudoword refixations ( $b = 0.00$ ,  $SE = 0.00$ ,  $t = 4.35$ ,  $p < .001$ ) and a  
296 significant interaction between them ( $b = 0.00$ ,  $SE = 0.00$ ,  $t = 5.92$ ,  $p < .001$ ), that is,  
297 participants made more refixations before responding to the left than to the right. No other  
298 effect or interaction was significant.



299

300 **Figure 2.** Estimated marginal means from the mixed models (EMMs) for saccade latencies  
 301 (A) and for saccade amplitude in Degrees of Visual Angle (B) showing the interaction  
 302 between Time (past vs future) and Side (left vs right) for words but not pseudowords. Error  
 303 bars represent within subjects' standard errors.

304

305 **Discussion**

306

307 Results replicate space-time congruency effects in a lexical decision task in which  
 308 temporal processing was implicit and responses were provided by lateralized eye  
 309 movements. Both saccade latency and saccade amplitude were affected. Leftward saccades  
 310 were initiated more quickly and were smaller in amplitude for past-tense words whereas  
 311 rightward saccades were quicker and smaller for future-tense words. Given that saccade

312 latency corresponds to the time needed to visually process the stimulus, make the lexical  
313 decision, and execute the motor response (Gilchrist, 2011), the space-time congruency effect  
314 observed for saccade latencies can be considered analogous to the congruency effect  
315 obtained previously for manual lexical decision times (Grasso et al., 2021). In contrast, the  
316 space-time congruency effect for saccade amplitude is more likely driven by lexical  
317 interference operating on metrical adjustment and motor programming of the saccadic  
318 response. As parameters of the saccade cannot be modified once it is initiated (e.g., Edelman  
319 et al., 2007; Gilchrist, 2011), this suggests that the calculation of the ballistic movement itself  
320 is affected by space-time congruency. Different amplitudes between congruent and  
321 incongruent trials show that the processing of the temporal content of words interferes with  
322 saccade programming.

323         As in our previous study (Grasso et al., 2021), these effects were not found for  
324 pseudowords, suggesting that they tap lexical access or lexical representations. These results  
325 further replicate our previous findings by confirming that the space-time congruency effect  
326 can be obtained even when the processing of the words' temporal information is not  
327 explicitly required to perform the task, suggesting that the key factor for obtaining this effect  
328 might be spatially directed movement *per se*.

329         Finally, the significant interaction between the temporal content of words and the  
330 direction of eye movements suggests that the lexical representation of words that refer to  
331 time contains spatially oriented information (see also; Hartmann et al., 2014; Stocker et al.,  
332 2016). Interference arises because, in the incongruent conditions, leftward or rightward  
333 movements engage spatially oriented motor networks that are incompatible with the left-  
334 right oriented spatio-temporal information associated with the lexical representation of the  
335 word. These results are consistent with the idea that the spatial representation of the  
336 temporal content of words derives from culture-dependent directional movements that are  
337 habitually produced during writing and reading (e.g., Boroditsky & Gaby, 2010; Fuhrman &  
338 Boroditsky, 2010; Oliveri et al., 2009). In the future, it would be informative to investigate to

339 what extent reading development or reading expertise determines the emergence of the  
340 space-time congruency effect.

341 Interestingly, the replication of the space-time congruency effect with eye  
342 movements also suggests that the spatial frame of reference used to distinguish between the  
343 left and the right space is centred on the median axis of the whole-body. To test further this  
344 hypothesis of a body-centered frame of reference engaged in the coding the spatio-temporal  
345 representation of words, one could replicate the experiment with another effector that is not  
346 involved in reading or writing, such as the foot.

347 To conclude, our results fit nicely with an embodied conception of language and  
348 time, by showing that directional movements of body parts through space are involved in  
349 the coding of past- and future-tense verbs.

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365 **Declarations**

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368 comments and suggestions.

369 **Conflicts of interest**

370 We have no known conflict of interest to disclose.

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375 University (A\*MIDEX).

376

377 **Availability of data, code, and materials**

378 According to the open science practices all data and script are available at  
379 <https://osf.io/5ehnc/>

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