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

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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**

97

98 *Participants*

99

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 gonttreraï, 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*

125

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.

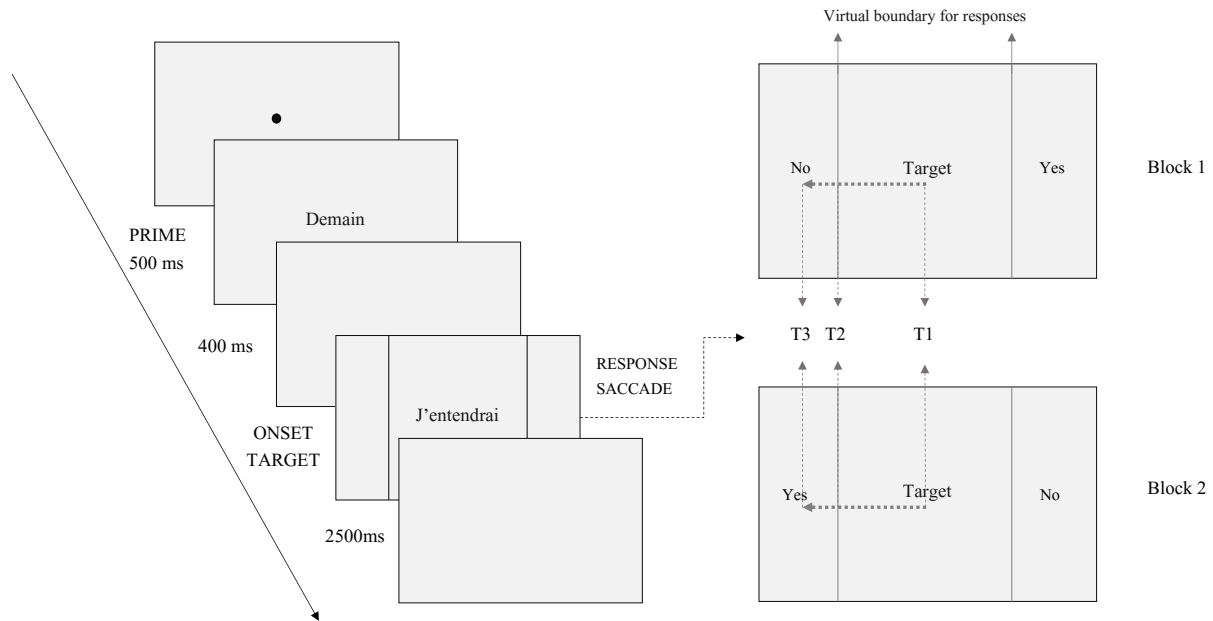
138

139 *Procedure*

140

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%)¹. 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 ± 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

¹ 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.

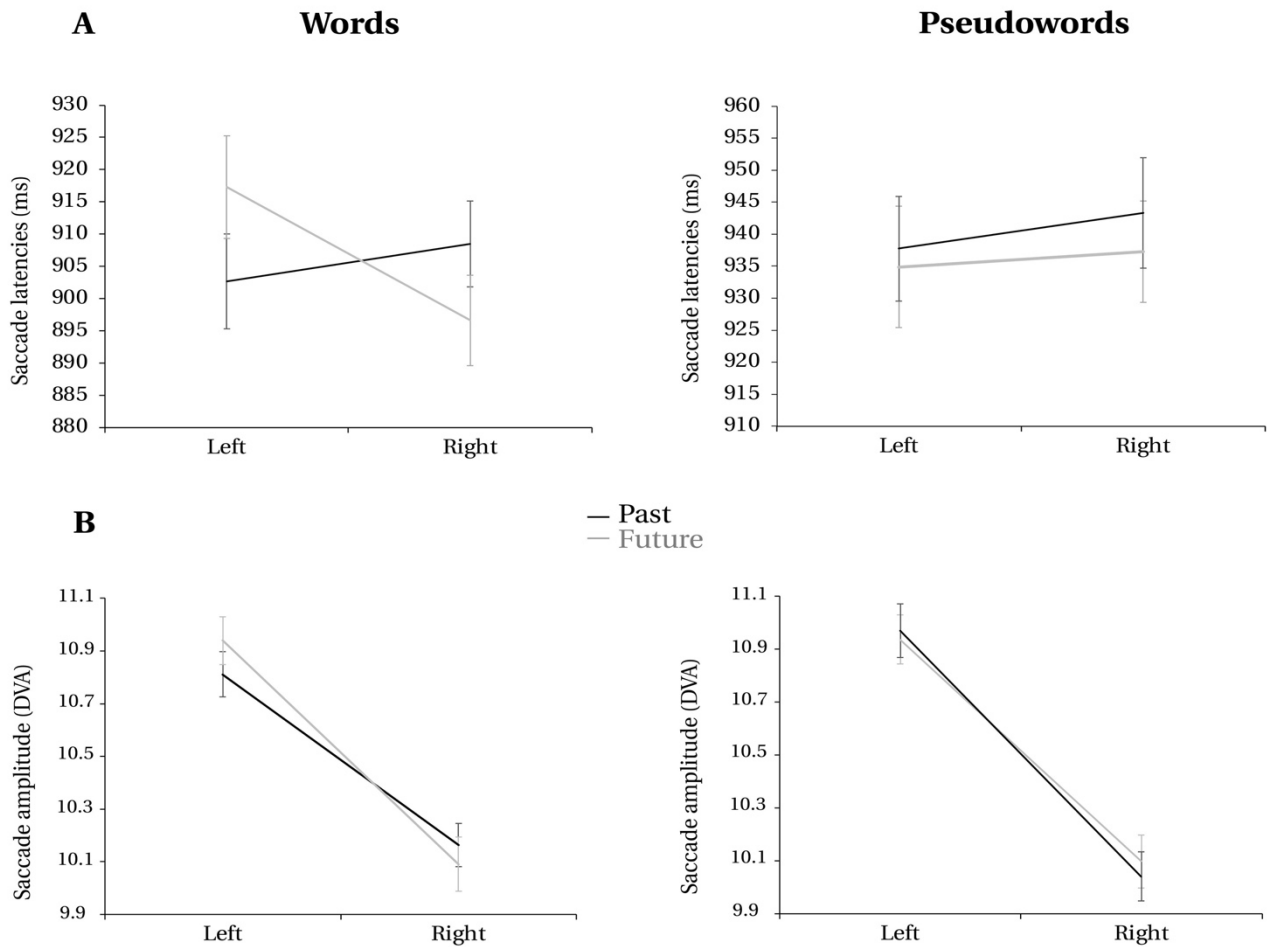
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284 *Pseudowords*

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**

366 **Acknowledgments**

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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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