Space–Time Congruency Effects Using Eye Movements During Processing of Past- and Future-Related Words

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Abstract

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

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

Introduction

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

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

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

Materials and Methods

Participants

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

Design and Stimuli

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

Apparatus

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

Procedure

The experiment was run in a quiet testing room. Participants were instructed to decide as rapidly and as accurately as possible whether the stimulus was a real French word or not (i.e., a lexical decision) by moving their eyes towards the left / right side of the screen. Half of the participants started with “yes” responses towards the left (yes-left) and half with “yes” responses towards the right (yes-right), and all participants switched response sides halfway through the experiment. Participants completed a short training session of 20 trials before each experimental block. Each participant saw a total of 80 words and 80 pseudowords in a pseudo-randomized order across two counterbalanced blocks (yes-right or yes-left). For the yes-right block, future-tense words were congruent with the MTL and past-tense words were incongruent (see Figure 1). In each block, there were 40 words and 40 pseudowords, half of each being conjugated in the past tense and half in the future. In the yes-left block, past-tense words were congruent and future-tense words were incongruent. At the beginning of the experiment, eye position was calibrated using a 9-point calibration grid. The experiment started once the training session was completed. Each trial started with a drift correction dot presented at the centre of the screen. Participants were instructed to fixate this dot, which triggered the onset of a prime stimulus: *hier* or *demain* ("yesterday" or "tomorrow") displayed for 500ms, followed by a 400ms blank screen and then finally by the stimulus (i.e., a word or pseudoword). The stimulus remained on the screen until the participants responded by making a saccade. Saccades that crossed the virtual left or right boundaries were considered as responses, whereas saccades that did not cross the boundaries were considered as refixations or microsaccades (depending on their amplitude). Saccade response side was automatically registered when the eyes crossed the left or right boundary. Responses time corresponded to saccade latency (latency between the onset of the stimulus and onset of the saccade). To assess the kinematic features of the saccade, we measured saccade amplitude expressed in degrees of visual angle. After each response, participants were instructed to fixate the central black dot in order to start the next trial. The time interval between the onset of the stimulus and the new fixation dot was 2500ms. A break was offered to participants every 20 trials. Half-way through the experiment (80 trials) participants were instructed to switch sides for yes/no responses. Each testing session lasted approximately 1 hour.

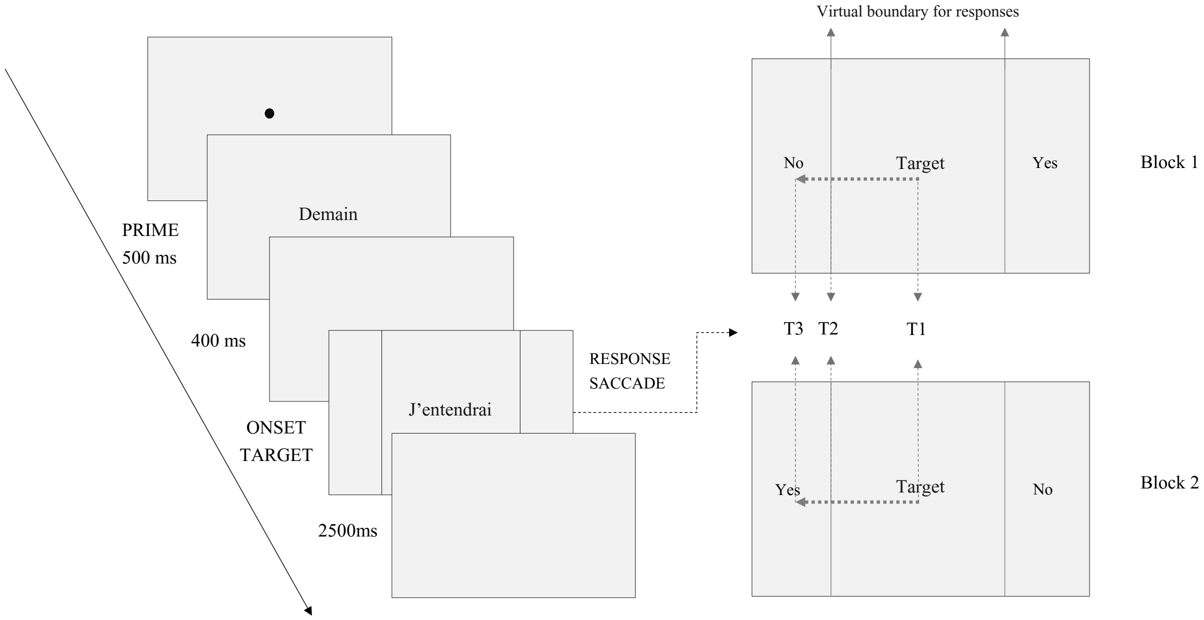

Figure 1. Task design. Once participants fixated the central dot, a prime (*hier* or *demain*, i.e., "yesterday" or "tomorrow") was displayed, followed by a word or pseudoword (e.g, *j'entendrai* as a future tense verb or *j'entendais* as a past tense verb). Participants made their lexical decision by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

Data analyses

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

Both saccade latency and amplitude were analyzed using linear Mixed Effect Models (LMEs) with participants and items as crossed random effects (Baayen, 2008; Barr, 2013). Note that the space-time congruency effect is indexed by the interaction between response side and verb tense. That is, when the side of response for a past-tense word switches from left to right from one block to the other, the word stops being congruent and, instead, becomes incongruent. Similarly, when the side of the response for a future-tense word switches from left to right, the word stops being incongruent and becomes congruent (see Figure 1). Data were fitted with lmer functions from the lme4 package (Bates et al., 2015) in the R statistical computing environment (Version 3.5.2; R Core Team, 2020). We report unstandardized regression coefficients, standard errors (SEs), and t values. Fixed effects were deemed reliable if $|t|$ was greater than 1.96 (Baayen, 2008). In a forward stepwise model selection procedure, fixed and random effects of the models were selected according to the Akaike Information Criterion (AIC; Akaike, 1973), the Bayesian Information Criterion (BIC; Schwarz, 1978) using the anova() function of the package lmerTest package (Kuznetsova et al., 2017) for model comparison. Therefore, fixed effects and random slopes were only included if they significantly improved the model parsimony (as assessed by the AIC/BIC). We built our models using the following procedure: we started with an empty model containing no fixed effect but a random intercept for participant and a random intercept for item. In a second step, fixed effects were selected using the forward stepwise selection procedure. Finally, we included a random slope for each of the selected fixed effects if it improved the model parsimony (as assessed by the AIC/BIC). Model assumptions were checked for each model using the check_model() function from the performance (Lüdecke et al., 2021) package. Following the procedure described by Brysbaert and Stevens (2018), we conducted power analysis based on 200 simulations with powerSim functions from the simR package (Green & MacLeod, 2016). We used the Satterwaithe method as implemented by the afex package (Singmann et al., 2021) for computing p-values. To create figures, we used the emmeans package (Lenth, 2021) and computed estimated marginals means (EMMs) for the interaction between response side and verb tense for each model (see Figure 2).

Results

Saccade latency and saccade amplitude were analysed for the 58 participants. We removed trials containing blinks (2.91%), trials with no-response (2.21%), trials with negative fixation duration (2.41%), trials with a total fixation duration below 100ms (anticipatory responses, 1.63%), and trials in which the initial position of the response saccade on the x-axis was outside the left-or-right boundaries (0.72%)[1]. Trials with latencies greater than the possible trial duration (i.e., above 2500ms) or less than 300ms (0.06%), and trials with saccade amplitude greater than 30 degrees and less than 2 degrees (0.20%) were also discarded. Finally, after removing incorrect response trials (3.91%) latency outliers were removed following the classic ± 2.5 standard deviations from the participants' mean response time (2.66%). Statistical analyses were conducted separately for words and pseudowords.

Words

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

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

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

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

Pseudowords

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

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

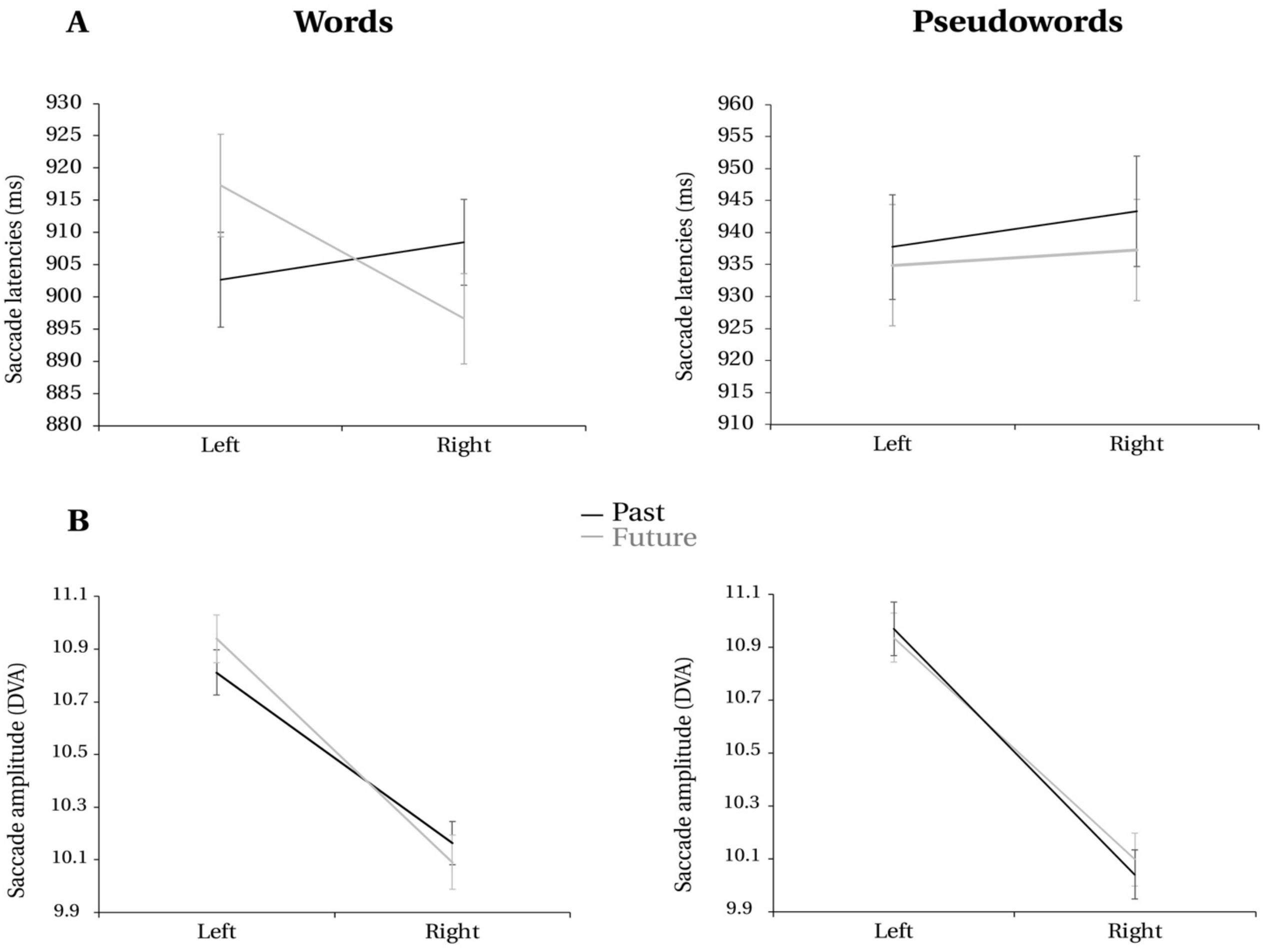

Figure 2. Estimated marginal means from the mixed models (EMMs) for saccade latencies (**A**) and for saccade amplitude in Degrees of Visual Angle (**B**) showing the interaction between Time (past vs future) and Side (left vs right) for words but not pseudowords. Error bars represent within subjects'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

Discussion

Results replicate space-time congruency effects in a lexical decision task in which temporal processing was implicit and responses were provided by lateralized eye movements. Both saccade latency and saccade amplitude were affected. Leftward saccades were initiated more quickly and were smaller in amplitude for past-tense words whereas rightward saccades were quicker and smaller for future-tense words. Given that saccade latency corresponds to the time needed to visually process the stimulus, make the lexical decision, and execute the motor response (Gilchrist, 2011), the space-time congruency effect observed for saccade latencies can be considered analogous to the congruency effect obtained previously for manual lexical decision times (Grasso et al., 2021). In contrast, the space-time congruency effect for saccade amplitude is more likely driven by lexical interference operating on metrical adjustment and motor programming of the saccadic response. As parameters of the saccade cannot be modified once it is initiated (e.g., Edelman et al., 2007; Gilchrist, 2011), this suggests that the calculation of the ballistic movement itself is affected by space-time congruency. Different amplitudes between congruent and incongruent trials show that the processing of the temporal content of words interferes with saccade programming.

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

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

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

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

Declarations

Acknowledgments

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Conflicts of interest

We have no known conflict of interest to disclose.

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Availability of data, code, and materials

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

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