Time is -ending: Sub-lexical information activates the horizontal Mental Time Line in word processing.

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Data availability statement

All the stimuli, the data that support the findings and the analyses involved in the present study are openly available in the OSF repository

https://osf.io/k4w7g/?view_only=df8ae2b101ed4392a1d5ef21d55f109c

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Abstract

The Mental Time Line (MTL) is a spatial on which earlier events are generally associated with the left space and later events with the right space. Accordingly, past- and future-related words receive faster responses with, respectively, the left and the right hand. Yet, it is currently unclear whether the MTL is activated by the whole word or whether it can be triggered by more subtle sub-lexical cues, such as verb-endings, and whether the activation of this spatial continuum is an automatic phenomenon. The aim of this study is to test whether verb-endings do bring conceptual information that is in turn capable to activate the MTL and whether this activation holds also when the temporal information is not explicitly processed. We designed three experiments. In Experiment 1, consisting of a temporal categorization task, and in Experiment 2, consisting of a lexical decision task, we tested Italian tensed verbs (*trov-avo* "I found", *trov-erò* "I will find") and pseudo-verbs (*trop-avo*, *trop-erò*). Results of Experiment 1 showed that both tensed verbs and pseudo-verbs were spatially coded on the MTL. Results from Experiment 2 showed that the MTL is activated by the verb-endings also when temporal information was task-irrelevant (i.e., lexical decision task). Experiment 3 further clarified that the spatial-temporal congruency effect does not emerge during the evaluation of an inhomogeneous set of stimuli (i.e., when adding to the stimuli time-unrelated fillers). Overall, the present findings indicate that sub-lexical strings carry specific semantic information that comes into play in the generation of spatial-temporal associations.

Keywords: Spatial-association effect; Mental Time Line; Psycholinguistics

1 Introduction

In everyday language, it is frequent to hear expressions such as "I had a *long* day at work", or "I will leave *shortly"*. When talking about time, a rather abstract domain, people often rely on the more concrete dimension of space (Lakoff, 1980). The use of spatial terms to communicate temporal information is more than just a linguistic metaphor. Indeed, recent evidence from cognitive science suggests that humans handle the concept of time by grounding it spatially (see Núñez and Cooperrider, 2013, for a review).

The association between spatial and temporal dimensions is supported by an increasing body of evidence. Although in language we do not use metaphoric expressions linking time with horizontal space, congruency effects between time and the horizontal space (left/right) have been reported for a variety of stimuli that have temporal connotations, such as duration (Vallesi, Binns, & Shallice, 2008) and onset timing (Ishihara, Keller, Rossetti, & Prinz, 2008), as well as linguistic stimuli that point to past or future events, such as adverbs and verbs (Flumini and Santiago, 2013; Aguirre and Santiago, 2017; Santiago et al., 2007; Torralbo et al., 2006; Grasso et al., 2021) or sentences (Ulrich and Maienborn, 2010). These studies showed that time is typically represented on the horizontal space along a "Mental Time Line" (MTL), which is a spatial continuum akin to a line, oriented from left to right, on which earlier events are generally associated with the left side of space and later events with the right space (for a review, see Bonato, Zorzi, & Umiltà, 2012).

The main experimental evidence in favor of the MTL is the association between the spatial response given to a stimulus, generally provided through hands, and its temporal connotation. Specifically, if the stimulus refers to the past, the responses are typically faster when provided with the left hand; on the contrary, if the stimulus refers to the future, it

typically elicits faster responses with the right hand (Casasanto and Bottini, 2014; Santiago et al., 2007; Torralbo et al., 2006; Ulrich and Maienborn, 2010). For instance, words and sentences pointing either to the past (e.g. “before”, “yesterday”) or to the future (e.g. “after”, “tomorrow”) receive faster responses with the left or right hand respectively, suggesting in turn that past- and future-related words activate a left-to-right oriented MTL (Santiago et al., 2007; Torralbo et al., 2006; Ulrich and Maienborn, 2010; Flumini and Santiago, 2013; Grasso et al., 2021). Mainly, the mentioned studies examined temporal adverbs and conjugated verbs. Potential events, expressed by the conditional verb mode [such as the Spanish *(si) él durmiera* “(if) he would sleep”], show a past-left, future-right congruency effect as well (Aguirre and Santiago, 2017). Spatial-temporal congruency effects are observed also when responding to past and future-related sentences (past: *Hanna reparierte gestern das Fahrrad*, “Yesterday, Hanna repaired the bike”; future: *Morgen früh unterschreibt der Chef den Antrag,* “The boss will sign the application tomorrow morning”.), suggesting that time-space associations are formed when processing the temporal connotation of sentences and not only when evaluating isolated words (Ulrich and Maienborn, 2010).

Even if there is a general consensus about such space-time associations at the lexical and sentence level, the picture is much less clear when looking at sub-lexical aspects. Indeed, studies focusing on the more subtle cues provided by inflectional suffixes (which are supposed to carry some temporal information) have so far led to contrasting evidence (Flumini and Santiago, 2013; Grasso et al., 2021).

It is known that sub-lexical morphological elements, such as suffixes regularly occurring at the end of tensed verbs, can be mapped into certain aspects of word meaning (e.g., Baayen, Milin, Đurđević, Hendrix, & Marelli, 2011; Amenta and Crepaldi, 2012;

Ulicheva, Marelli & Rastle, 2021). Indeed, the time-related dimension in verbs like the Spanish *cant-amos* ("we sang'') and *cant-aremos* ("we will sing") could be carried by the lexical representations themselves (*cantamos* and *cantaremos*) but, in principle, the same piece of information could be cued by just the sub-lexical strings *-amos* and *-aremos* (see Marelli, Traficante, & Burani, 2020): in fact, the word onset *cant-* does not provide, by itself, any time-related cue, which is rather expressed by means of the suffixes *-amos/-aremos.* It is likely that the sub-lexical element, the suffix, typically appearing at the end of the verb, may alone provide semantic information (Clahsen, 1999; Baayen, Dijkstra & Schreuder, 1997). In line with these considerations, influential models of word processing (Plaut and McClelland, 1993; Harm and Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Baayen, Milin, Đurđević, Hendrix, & Marelli, 2011), theorized and demonstrated that sub-lexical elements are informative cues that help to activate (or discriminate between) meanings.

However, such a conceptual counterpart of morphology has been rarely addressed in the literature on space-time effects. To the best of our knowledge, only two studies (Flumini and Santiago, 2013; Grasso et al., 2021) had previously attempted to investigate the activation of the MTL in relation to inflectional suffixes appearing in meaningless strings (i.e., pseudo-verbs). However, while in both studies a temporal-congruency effect was observed when testing participants in a temporal-categorization experiment, the effect could not be replicated using a more shallow task where tense was irrelevant, namely a lexical decision task. This difficulty in observing the phenomenon in the context of a lexical decision task might depend on the associations between temporal information and sub-lexical units being too weak to be observed in such a shallow condition. That is, without, on the one hand, the chance to rely on familiar, semantically rich, units, and, on the other hand, a task forcing

them to focus on time, participants would produce responses unaffected by temporal information. In fact, these circumstances could have been further aggravated by the varied item lists employed by Flumini and Santiago (2013) and Grasso et al. (2021). Crucially, in Grasso and colleagues, the French suffix-*ais*, characterizing the first-person singular of the past tense employed in the study, also serves as a nominal suffix, typically to indicate geographic provenience (e.g., *Franç-ais*, "French"). In the French corpus frWaC [1] (Baroni et al., 2009) there are about 700 nouns ending with -*ais* and indicating geographical origins. Therefore, in French, the sub-lexical string -*ais* is systematically associated with different types of information (both time- and geography-related). This aspect may have caused the lack of activation of the MTL. In Flumini and Santiago (2013) several different inflectional affixes were employed as the ending of pseudowords, so that within the experiment several rather different endings were expected to carry temporal information. The inhomogeneity of the item list could have affected the reliance on sub-lexical cues, weakening the time-congruency effect enough for it to disappear in the lexical-decision condition. The lack of cross-task replicability, along with these possible alternative explanations, call for further investigations of the potential temporal congruency effect for inflected pseudo-verbs, as well as their dependence on specific experimental demands.

The aim of the present study is to investigate whether a spatial-temporal congruency effect can be elicited by sub-lexical elements, and whether such an effect can be detected when the tense of the stimuli is not relevant to the completion of the task. In this study, we employed both existing past and future conjugated Italian verbs as well as pseudo-verbs whose endings corresponded to the typical past and future endings of Italian verbs. In Italian, inflectional word-endings such as -*avo* and -*erò* in the verbs *cant-avo* ("I sang") and

[1] The frWaC corpus (1.3 billion words) is a French text corpus collected from the .fr domain with using medium-frequency words from the Le Monde Diplomatique corpus and basic French vocabulary lists as seeds.

cant-erò (“I will sing”) are regularly associated with the past and future tense, respectively. If past and future endings would activate spatial-temporal congruency effects in pseudo-verbs as well as existing conjugated verbs, we would conclude that grounded phenomena, such as the activation of the Mental Time Line, can be elicited by sub-lexical elements alone; indeed, pseudo-verbs cannot be represented as whole words and hence any effect observed in relation to them should be attributed to the information carried by their endings.

To test the task-independent activation of the MTL we included, along with an experiment in which tense is a relevant dimension of the task at hand (Experiment 1), also an experiment in which the task can be completed without considering the tense of the stimuli (Experiment 2). To further test the automatic activation of the MTL, a third experiment is reported, in which verbs and pseudo-verbs were presented with time-unrelated filler stimuli in a lexical decision task.

2 Experiment 1

2.1 Methods

2.1.1 Participants

Thirty-nine students (mean age= 22.4, S.D.=4.1; females= 28, males=11) from the University of Milan-Bicocca took part in the study for course credits. The number of participants was determined a priori following the guidelines by Brysbaert & Stevens (2018), developed to design a properly powered reaction time experiment with repeated measures and mixed-effects analysis. None of them reported any visual or linguistic impairment. All the participants were Italian native speakers. Before their participation, they were informed of the experimental procedures and all of them consented to take part in the experiment, which was approved by the local ethics committee (RM-2020-294).

2.1.2 Materials and design

A hundred verb stems, such as *mang-* , Italian stem of the verb "to eat", or *dorm-* , stem of the verb "to sleep", were conjugated to the imperfect past tense (*mangi-avo*, "I ate"; *dorm-ivo,* "I slept") and to the simple future tense (*mang-erò*, "I will eat"; *dorm-irò*, "I will sleep"); past- and future-conjugated verbs appeared to the first person singular and plural (*io* "I", *noi* "we") and to the third person singular and plural (*lui/lei* "he/she", *loro* "they"), for a total of 800 stimuli. Since Italian is a pro-drop language, i.e., the personal pronoun can be omitted from the verb form, during the experiment verbs were presented without being preceded by the pronoun.

The same hundred verb stems were modified into pseudo-stems, i.e., non-existing stems were obtained by changing one phoneme of the stem (either a vowel or consonant). For instance, starting from the existing stem *trov-*, stem of the verb *trov-are* ("to find"), we changed the consonant */v/* into the consonant */p/*, producing the non-existing pseudo-stem *trop-*. The pseudo-stems were all phonologically plausible and orthotactically acceptable in Italian. We then added to the pseudo-stem *trop-*, the past ending *-avo* ("tropavo"), and the future ending *-erò* ("troperò"). The pseudo-verbs then appeared in the first person singular and plural and in the third person singular and plural, both in the past and future forms, in analogy with real verbs (Table 1).

In conclusion, we employed 100 verb stems which were modified in 100 pseudo-stems. By adding to the stems and pseudo-stems the past and the future verb -endings and making them appear to the 1st person singular and plural and 3rd person singular and plural, we obtained 800 verbs and 800 pseudo-verbs according to the following schema: 100

(stems/pseudo-stems) x 2 (past/future) x 4 (1st person singular and plural, 3rd person singular and plural).

Table 1. Example of the stimuli involved in the experiment. The pattern was repeated for 100 stems and for 100 pseudo-stems.

Stem/ pseudo-stem	1st sing. past	1st sing. future	3rd sing. Past	3rd sing. Future	1st plur. past	1st plur. future	3rd plur. Past	3rd plur. future
TROV-	trov-avo	trov-erò	trov-ava	trov-erà	trov-avamo	trov-eremo	trov-avano	trov-eranno
TROP-	trop-avo	trop-erò	trop-ava	trop-erà	trop-avamo	trop-eremo	trop-avano	trop-eranno

The stimuli were divided into four item lists. Each item list contained 400 stimuli, 200 verbs and 200 pseudo-verbs, in which stems and pseudo-stems were counterbalanced in order to avoid facilitation effects of some sort (for instance, if one list contained the past verb *trovavo*, the same list did not contain the pseudo-past-verb *tropavo*, but it rather contained the pseudo-verb *dolmivo*, which was created from a different stem). Each participant was presented with one list only. The lemma frequency of each existing verb was collected through the database SUBTLEX-IT (Crepaldi, Amenta, Mandera, Keuleers, & Brysbaert, 2016) and was balanced across the lists (one-way ANOVA test: F=.04, p=.98).

All the stimuli are openly available in the OSF repository https://osf.io/k4w7g/?view_only=df8ae2b101ed4392a1d5ef21d55f109c

2.1.3 Procedure

The experiment was created using the software Psychopy 3 (Peirce et al., 2019) and it was run online and hosted on the Pavlovia platform (https://pavlovia.org/). Participants

were asked to evaluate whether the stimulus they were presented (both verbs and pseudo-verbs) appeared to the past tense or to the future tense, by pressing either the *A* or *L* keys on the keyboard.

Before the experiment, an instruction page explained the task. Participants were instructed to evaluate whether the verbs that appear on the screen referred to the past tense or to the future tense by pressing the A and L keys on the keyboard. They were required to be as fast and as accurate as possible in their answers. One more instruction page was added before the block that involved pseudo-verbs, which explained that the task would have involved a non-existing language, whose verbs were conjugated in a way that was very similar to Italian, even though they were meaningless to them.

Each participant was presented with one of the four lists (see above). The experiment included two experimental blocks, each containing either verbs or pseudo-verbs. Order of presentation (verbs first or pseudo-verbs first) and response keys (A=past, L=future and *vice versa*) were counterbalanced between participants. Response keys were counterbalanced between the two blocks as well, namely if in the first block participants were instructed to respond to past stimuli with the *A* key and to future stimuli with the *L* key, the opposite pattern of responses was required in the second block. Participants used a qwerty keyboard; hence the keys *A* and *L* were pressed with the left and right hand, respectively.

After the consent form and the instruction page(s), participants completed 8 practice trials to familiarize themselves with the task. After having completed the first block, participants were allowed to take a 5-minute break. Before starting the second block, participants performed 8 more practice trials to familiarize themselves with the new items and the new response keys. Stimuli were presented written in Arial font with a 33-point size in the middle of the screen (0, 0). The strings were presented in white (255,255,255) color on

a gray (125,125,125) background. A fixation cross (150 milliseconds) preceded the presentation of each stimulus. Stimuli remained on the screen until key pressure.

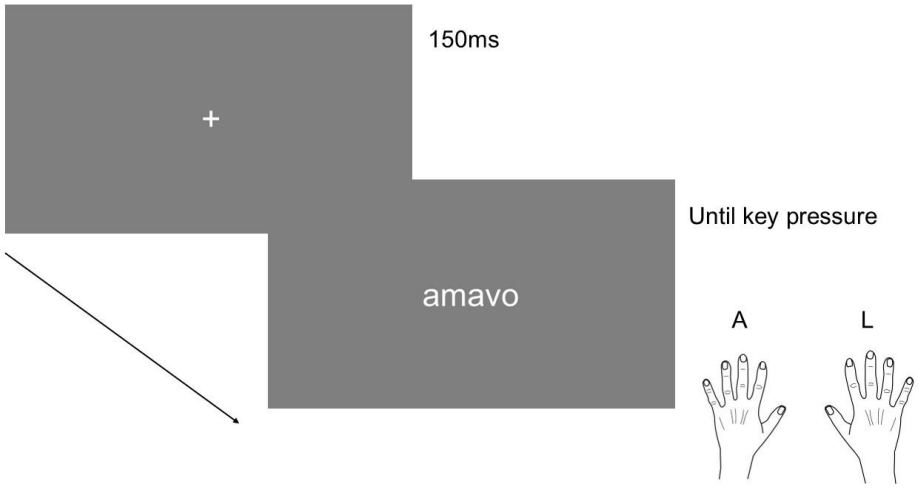

Figure 1. Schematic graphical representation of the trial presentation procedure.

2.2 Analyses and Results

16500 data points were collected in total, matching the recommendation for a properly powered mixed-effects analysis of 1600-datapoints-per-condition (Brysbaert and Stevens, 2018). One participant was excluded due to the low level of accuracy (=.6), generating a data loss of 2.5% of the total number of observations. All the other participants had accuracy >.9.

To analyze the results, we ran a linear mixed-effects model with log-transformed response times as dependent variable, a three-way interaction between the tense of the stimuli (past/future), the responding hand (left/right) and the stimulus category (verbs/pseudo-verbs) as predictors, and items and subjects as random intercepts. The analyses were run using the packages “lme4” (Bates, Mächler, Bolker, & Walker, 2015) and “lmerTest” (Kuznetsova, Brockhoff, & Christensen, 2017). The output of the model showed

that the interaction between tense, hand used and category of the stimuli did not significantly predict the response times (t=-.048, p=.962).

We hence simplified the model and ran a linear mixed-effects model with log-transformed response times as the dependent variable, and three two-way interactions as predictors (the first between tense and hand used, the second between tense and the stimulus category, the third between hand and stimulus category), and items and subjects as random intercepts. Removing the three-way interaction did not significantly affect model fit (X^2 (1, N = 11) = .002, p = .96).

Table 2. Fixed-effects of the model including log-transformed response times as dependent variable, three two-way interactions between: tense*hand, tense*category, hand*category as predictors and items and subjects as random intercepts.

	Estimate	Std. Error	Df	t-value	p-value
(intercept)	6.759	.027	43.171	242.907	<.001
Hand	.018	.008	12290	2.146	.03
Tense	-.102	.012	2501	-9.483	<.001
Category	-.022	.011	2445	-2.074	.038
tense*hand	-.035	.009	12250	-3.569	<.001
tense*category	.018	.013	1575	1.333	.182
hand*category	.003	.009	12240	.327	.743

Results showed that the interaction between the tense of the stimulus and the hand used to provide the response significantly predicted the response times (t=3.56, p<.0001) while the interactions between the tense and the category and between the hand and the category were not significant (Table 2).

This significant interaction is represented in Figure 2a: responses to past-related stimuli were faster when provided with the left hand, while responses to future-related stimuli were faster when provided with the right hand.

We then calculated the difference in reaction times between the responses provided with the right hand and the responses provided with the left hand and reported the means for past and future items, to more effectively represent the reported spatial-temporal congruity effect (Figure 2b).

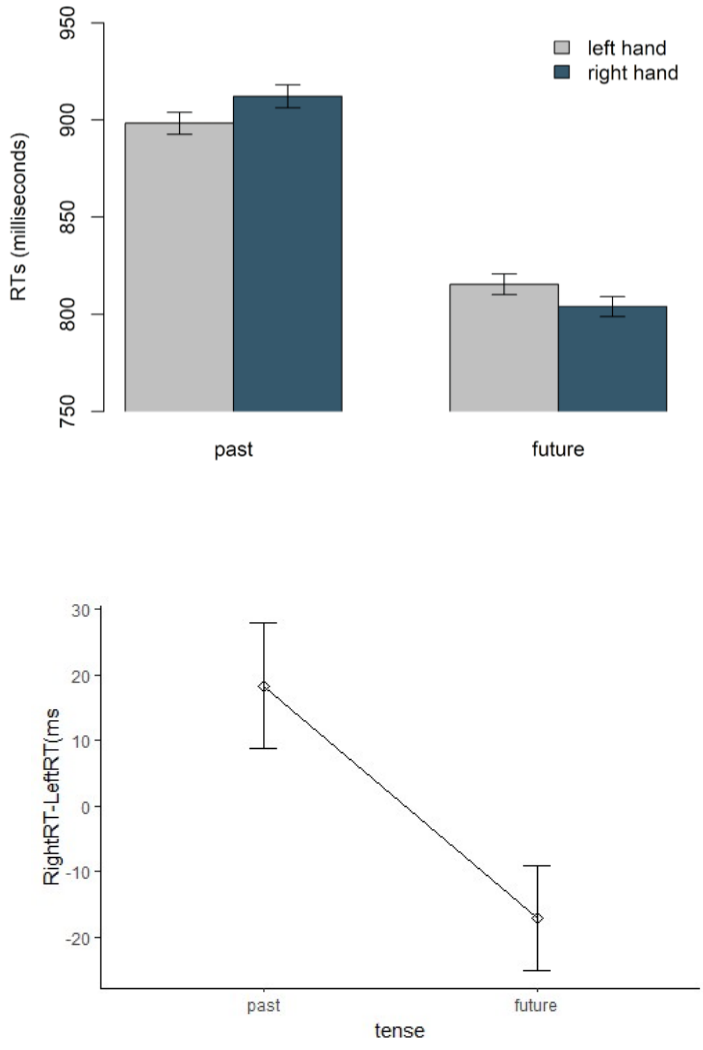

Figure 2a. Means of the response times for past- and future-related stimuli when provided with the left hand and the right hand.

Figure 2b. Difference in response times (milliseconds) between the responses provided with the right hand and

responses provided with the left hand for past and future stimuli.

Average response times (Table 3) showed that stimuli (i.e., verbs and pseudo-verbs) referring to the past were responded to faster with the left hand rather than with the right hand, with the opposite pattern for the right hand. Similarly, verbs and pseudo-verbs whose endings were conjugated to the past received faster responses when the response was provided with the left hand rather than with the right hand, with the opposite pattern for the right hand.

Table 3. Means of the response times (in milliseconds) and Standard Errors of the Mean split for verbs and pseudo-verbs, conjugated to the past and to the future tense.

	Left hand	Right hand
Past verbs	883.5 (7.9 SEM)	904.3 (7.6 SEM)
Future verbs	814.1 (7.2 SEM)	800.6 (7.1 SEM)
Past pseudo-verbs	913.3 (8.0 SEM)	920.9 (9.2 SEM)
Future pseudo- verbs	817.2 (7.9 SEM)	807.5 (7.3 SEM)

The same statistical analyses were applied to accuracy data, but the results did not show any significant effect[2].

2.3 Discussion

The goal of Experiment 1 was to investigate whether spatial-temporal congruency effects can be elicited by sub-lexical elements. To test this hypothesis, we designed a

[2] Generalized linear mixed-effects models (GLMMs), with analogous fixed and random effects of the models employed for RTs, were used to analyze the accuracy data. Results showed that neither a three-way interaction between tense, hand and category (tense*hand*category: z=-1.5; p=.12) nor any of the three two-way interactions (tense*hand, tense*category, hand*category) predicted accuracy data (tense*hand: z=.21, p=.83; tense*category: z=-.16, p=.87; hand*category: z=1.7, p=.08).

categorization task employing as stimuli past and future conjugated verbs as well as past and future pseudo-verbs, namely non-existing verbs whose endings were the same as past and future conjugated verbs.

Response times results showed a facilitation effect when past-tense stimuli were responded to with the left hand and when future-tense stimuli were responded to with the right hand, with respect to when the opposite mapping was applied. The effect was found in relation to both existing conjugated verbs and pseudo-verbs, meaning that the tense expressed through word-endings triggered the spatial-temporal association. The effect was independent from the stimulus lexicality, indicating that it was not triggered by a whole word representation, considering that pseudo-verbs cannot activate such representation.

Thus, we demonstrate that sub-lexical elements, such as verbal suffixes, carry sufficient semantic information to activate spatial-congruency phenomena that are typically observed in relation to the more complex temporal information expressed by whole words or even by sentences (Casasanto & Boroditsky, 2008; Milin et al., 2018; Santiago et al., 2007; Torralbo et al., 2006; Ulrich & Maienborn, 2010; Weger & Pratt, 2008). Nonetheless, this kind of effect is generally observed when the task directly requires participants to process the temporal dimension of the stimuli, but when the tense is not the focus of the task the spatial-temporal congruency effect tends to disappear (Aguirre & Santiago, 2017; Santiago et al., 2007). This seems to suggest that the MTL is activated only when explicitly evaluating the temporal dimension of the verb stimuli, otherwise, no spatial-temporal compatibility effect is triggered (for a meta-analysis, see von Sobbe, Scheifele, Maienborn, & Ulrich, 2019). Having considered this evidence, we were interested in investigating whether a spatial-temporal compatibility effect could be identified also when the task did not explicitly concern the tense of our stimuli. Testing these effects across-task is crucial in order to

understand to what extent spatial-temporal association effects and, more in general, grounded effects may occur in everyday communication (Ostarek & Huettig, 2019). Indeed, grounded effects in relation to word processing could occur only in the situations in which a specific aspect of word meaning is taken into consideration or may occur more generally, independently from the kind of task adopted. If the spatial-temporal effect requires the consideration of the temporal dimension, the effect should be linked to the specific task; but if the spatial-temporal association effect is observed also when performing tasks in which the temporal dimension is not relevant, the effect should be linked to an automatic activation of the MTL.

Therefore, we designed a second experiment in which the stimuli were the same as the first one, but the task consisted of a lexical decision. In a lexical decision, participants' attention is moved to the lexicality of the stimuli rather than to their temporal dimension, which becomes irrelevant for solving the task. If the results show a compatibility effect in the lexical decision task, this would suggest that the effect that we observed in Experiment 1 is robust and independent from the type of task used; on the other hand, if the spatial-temporal association effect disappears when the task does not regard the tense of the stimuli, this would suggest that this kind of effect is exclusively triggered by the type of task involved. Finding a similar effect also in Experiment 2 would indicate that the spatial-temporal congruency effect in relation to verb -endings can be generalized as an automatic mechanism, instead as an effect occurring in specific situations.

3 Experiment 2

3.1 Methods

3.1.1 Participants

Thirty-seven students (mean age=21.8, S.D.=4.4; females= 27, males=10) from the University of Milan-Bicocca took part in the present experiment for course credits. Participants that took part in this experiment were different from the participants of the previous experiment. As in Experiment 1, the number of participants was determined a priori following the guidelines proposed in Brysbaert and Stevens (2018). None of them reported any linguistic disorder. All the participants were Italian native speakers.

3.1.2 Materials and design

We used the same stems and pseudo-stems presented in Experiment 1. The only difference concerned the inflection to the verbal person since we decided to consider the first person singular (*io*, "I") only, in order to reduce the number of stimuli involved. This decision is motivated by the fact that we decided to design a within-participants experiment. Similarly to Experiment 1, stimuli were created by adding to the hundred stems and hundred pseudo-stems an imperfect past verb-ending (e.g., -avo) and a simple future verb-ending (e.g., -erò). We thus obtained 200 conjugated verbs and 200 pseudo-verbs, for a total of 400 stimuli. We divided the 400 stimuli into two lists, in order to avoid the coexistence of verbs and pseudo-verbs that were obtained from the same stem (for instance, if list 1 contained the verb *cred-evo* ("I believed"), the pseudo-verb *crid-evo*, which was obtained by the manipulation of the same stem, appeared in list 2). Each participant was presented with both lists, in two separate blocks. The order of presentation of the lists (list 1=block1, list 2=block2 and the opposite mapping) and the hands used to respond (A=words, L=pseudo-words first and *vice versa*) were counterbalanced between the participants. All the stimuli are openly available in the OSF repository https://osf.io/k4w7g/?view_only=df8ae2b101ed4392a1d5ef21d55f109c

3.1.3 Procedure

The experiment was created with the software Psychopy 3 (Peirce et al., 2019) and run online hosted on the Pavlovia platform (https://pavlovia.org/). Before the experiment, an instruction page described the task. Participants were asked to judge whether the stimulus displayed was a word that existed in the Italian language or whether it was not an existing word, by pressing the A and L keys on the keyboard. They were instructed to be as fast and as accurate as possible in their responses.

Participants were instructed to use the left hand to press the *A* key and the right hand to press the *L* key on a qwerty keyboard. The response keys were counterbalanced between blocks. For instance, if a participant was instructed to use *A* to indicate that the stimulus was an existing word and *L* to indicate that it was not a word in the first block, they will be instructed to use the reverse order in the second block and vice-versa. Before starting the experiment, one instruction page described the task. Participants were informed that they were asked to evaluate whether the string of letters that appeared on the screen was an existing word in the Italian language or not, by pressing the keys A and L on the keyboard. After the instruction page, participants completed eight practice trials to familiarize with the task. After the completion of the first block, they were allowed to take a short break. Before starting the second block, participants performed eight more practice trials to familiarize themselves with the new response keys. Verbs and pseudo-verbs were presented written in Arial font with a 33-point size in the middle of the screen (0, 0). The strings were presented in white color (255,255,255) on a gray (125,125,125) background. A fixation cross (150 milliseconds) preceded the presentation of each stimulus (see Figure 1). Stimuli remained on the screen until key pressure.

3.2 Analyses and Results

A total number of 14800 datapoints were collected, matching the recommendation for a properly powered mixed-effects analysis of 1600-datapoints-per-condition (Brysbaert and Stevens, 2018). All the participants successfully completed the experiment, with an accuracy score above .9 for each of them.

To analyze the results concerning the response times, we ran a linear mixed-effects model with log-transformed response times as the dependent variable, a three-way interaction between the tense of the stimuli (past/future), the hand used to provide the response (left/right) and the category of the stimuli (verbs/pseudo-verbs) as independent variables, and items and subjects as random intercepts. The data were analyzed using the packages “lme4” (Bates et al., 2015) and “lmerTest” (Kuznetsova et al., 2017). The results showed that the three-way interaction did not significantly predict response times (t=.03, p=.97).

We then ran a linear mixed-effects model with log-transformed response times as the dependent variable, three two-way interactions as predictors, the first between the tense and the hand used to provide the response, the second between the tense and the category of the stimulus, the third between the hand and the category, as predictors, and items and subjects as random intercepts. Removing the three-way interaction did not significantly affect model fit r (X^2 (1, N = 11) = .0008, p = .98).

Results (Table 4) showed that the interaction between the tense and the response hand significantly predicted the response times (tense*hand: t=-2.2, p=.034), together with the interaction between the hand used to give the response and the category of the stimulus (hand*category: t=5.5, p<.001), consistently with the means reported in Table 4. The

interaction between hand and category did not predict the response times (tense*category: t=0.9, p=.36).

Table 4. The table showed the output of the linear mixed-effects model with log-transformed response times as the dependent variable, three two-way interactions (tense*hand, hand*category, tense*category) as independent variables, and items and subjects as random intercepts.

	Estimate	Std. Error	df	t-value	p-value
(Intercept)	6.633	.023	48.360	281.028	<.001
Tense	-.037	.012	485	-3.022	.002
Hand	.017	.007	13360	2.433	.015
Category	.076	.012	487	6.096	<.001
tense*hand	-.018	-.008	13360	-2.112	.034
tense*category	.014	.016	381	0.899	.369
hand*category	.046	.008	13360	5.5	<.001

The results showed that past-related stimuli were responded to faster with the left hand and future-related stimuli were responded to faster with the right hand, rather than with the opposite pattern (Figure 3a). As in Experiment 1, we calculated the difference in reaction times between the responses provided with the right hand and the responses provided with the left hand and reported the means for past and future items (Figure 3b).

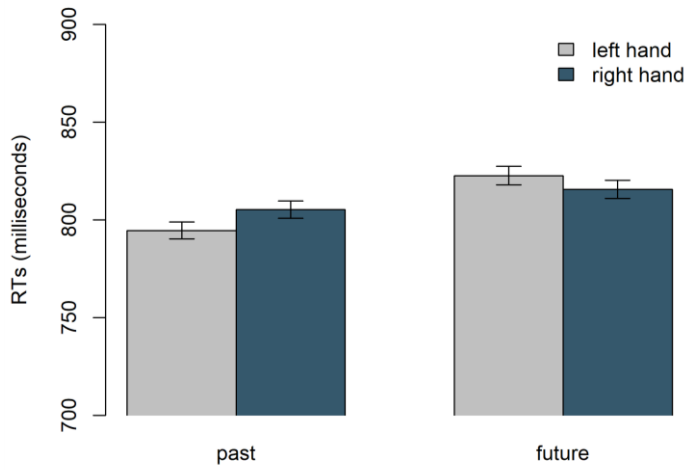

Figure 3a. Means of the response times for past and future stimuli when provided with the left hand vis-à-vis with the right hand.

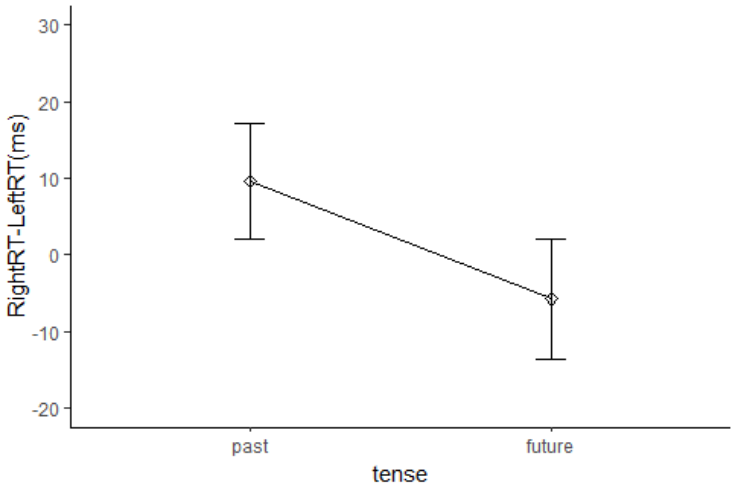

Figure 3b. Difference in response times (milliseconds) between the responses provided with the right hand and responses provided with the left hand for past and future stimuli.

Moreover, results showed faster responses to verbs when provided with the left hand via-à-vis the right hand, and faster responses to pseudo-verbs when provided with the right hand vis-à-vis the left hand (Figure 4).

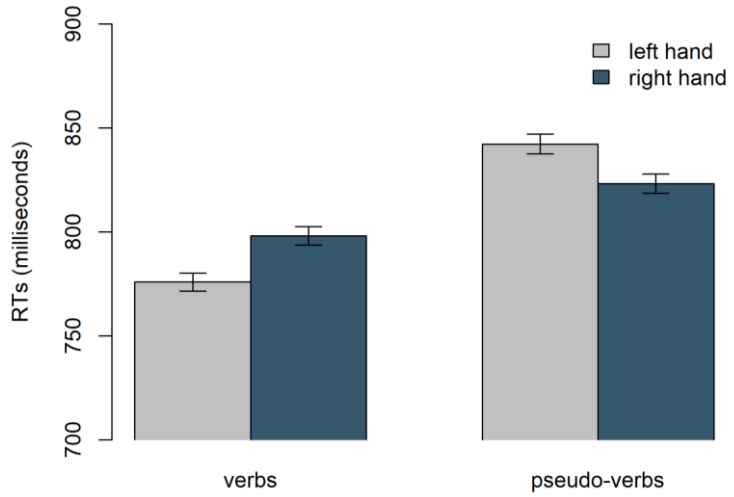

Figure 4. Means of the response times for verbs and pseudo-verbs with the left hand and the right hand.

From the means of the response times split for verbs and pseudo-verbs, it can be noticed that verbs show facilitation effects when the responses were given with the left hand, while pseudo-verbs show facilitation effects for responses given with the right hand. Moreover, verbs show an association between the past tense and left hand, while pseudo-verbs show an association between future-related stimuli and the right hand (Table 5). This general pattern emerges from the conflation of the two interactions reported above.

Table 5. Means of the response times (in milliseconds) and Standard Errors of the Mean split for verbs and pseudo-verbs, both relating to the past and to the future.

	Left hand	Right hand
Past verbs	759.1 (5.8 SEM)	791.3 (6.2 SEM)
Future verbs	793.2 (6.4 SEM)	805.4 (6.3 SEM)
Past pseudo-verbs	831.6 (6.5 SEM)	820.1 (6.3 SEM)
Future pseudo- verbs	853.3 (6.9 SEM)	826.5 (6.8 SEM)

The same statistical analyses were applied to accuracy data, but the results did not show any significant effect[3].

3.3 Discussion

The aim of Experiment 2 was to investigate whether the spatial-temporal association effect that we observed in Experiment 1 could be replicated also when the temporal dimension of the stimuli was irrelevant to the task. To reach this goal, we designed an experiment in which the same stimuli as Experiment 1 were involved, but the task concerned the lexicality of the stimuli rather than the temporal information they expressed. In particular, the task consisted in determining, by pressing keys on the keyboard with either the left or the right hand, whether a stimulus was an existing word in Italian or not. Results showed that the interaction between the tense of the stimuli and the hand used to provide the responses significantly predicted the response times, even though the task did not directly address the temporal dimension of the stimuli. This finding indicates that the spatial-temporal congruency effect driven by sub-lexical elements is observed also when participants are not asked to explicitly evaluate the temporal dimension of the stimuli and, thus, that the MTL is active also when not explicitly elicited.

Interestingly, we observed that verbs received faster responses with the left hand and pseudo-verbs received faster responses with the right hand. One possible explanation of this pattern of results can be linked to the lexical status of the stimuli (existing word vs. non-existing word). Hutchinson and Louwerse (Hutchinson and Louwerse, 2014) indeed, reported

[3] Data on accuracy were analyzed as in Experiment 1. Results showed that neither a three-way interaction between tense, hand and category ($z=-.19$; $p=.84$) nor the two-way interactions between tense and hand ($z=.42$, $p=.66$) and between hand and category ($z=-.71$, $p=.47$) predicted accuracy. Contrarily, the interaction between category and tense predicted accuracy ($z=2.5$, $p=.01$).

that low and high frequency words are subjected to spatial compatibility effects, similarly to tense-related words and quantity-related words (SNARC effect, Dehaene, Bossini, and Giraux, 1993). Precisely, high frequency words typically receive faster responses with the left hand and low frequency words typically receive faster responses with the right hand. Considering that existing verbs are associated to a frequency value, but pseudo-verbs have, to all intents and purposes, a frequency of 0, this could have led to a response-side compatibility effect in the present results. Another possible interpretation might be that, beyond the time-related dimension of verbs, participants activated a spatial representation of the existing *versus* non-existing category. Of course, the task explicitly asked whether the stimulus belonged to the category of existing or the category of non-existing entities and, in this specific context, the mental representation of the category followed a spatial horizontal alignment. Following this interpretation, which is framed within the ATOM theory by Walsh (2003), it might be postulated that also existing and non-existing categories are conceived as mental magnitudes (Walsh, 2003) and thus are spatially conceived.

We conclude that the spatial-temporal congruency effect, according to which past-conjugated verbs and past-related pseudo-verbs show faster responses with the left hand and future-conjugated verbs and future-related pseudo-verbs are responded to faster with the right hand, can be observed also when the task is not explicitly related to the temporal dimension of the stimuli. However, previous findings often reported a failure in the observation of the effect when time was task-irrelevant, questioning the automaticity of the MTL activation (Aguirre and Santiago, 2017; Santiago et al., 2007; Flumini and Santiago, 2013; Grasso et al., 2021; Ulrich et al., 2012; Ulrich and Maienborn, 2010; see von Sobbe et al., 2019 for a systematic review and metanalysis. For an investigation on the automaticity of the STEARC effect on non-linguistic stimuli see also Mariconda et al., 2022).

The difference between the findings previously reported in the literature (i.e., with no evidence about a horizontal MTL when time was not the relevant dimension) and our findings could be attributed to the kinds of stimuli employed. Indeed, the study by Santiago and colleagues (2007) and the study by Aguirre and Santiago (2017) employed different types of past and future related words in their set of stimuli, such as tensed verbs (similar to the one involved in the present experiment), adverbs ("yesterday", "tomorrow") and nouns ("past", "future"). The heterogeneity of the word classes of the stimuli could have led to an interference in detecting the spatial-temporal association in the experiments in which the temporal information was not a relevant dimension to perform the task. This interference between different kinds of stimuli may have caused the weakening and the disappearance of the effect. This explanation would also apply to Flumini and Santiago (2013) and Grasso et al. (2021). Although in these cases only verbs where used, the variety of affixes considered (Flumini and Santiago, 2013) and the inconsistent association between the employed affixes and temporal information in language experience (Grasso et al., 2021) could have made the participant less reliant on sub-lexical information. As a consequence, in the more shallow lexical decision task, the temporal information that endings were supposed to convey had no observable impact. In the other two mentioned studies (Ulrich and Maienborn, 2010; Ulrich et al., 2012), materials consisted of past and future related sentences, which are more complex to control with respect to stimuli internal consistency than isolated words.

Such interpretations of previous results suggest that time-congruency effects are substantially affected by the composition of the item list, especially when the phenomenon under investigation is already likely to be weakened (as in the case of pseudo-verbs). If that is the case, we would expect that the inclusion of time-irrelevant items will make sub-lexical units less reliable as cues for temporal information, in turn weakening the time-congruency

effect. This was tested in Experiment 3, in which we again administered a lexical decision task, but stimuli consisted of verbs, pseudo-verbs and time-unrelated nouns.

4 Experiment 3

4.1 Methods

4.1.1 Participants

Fifty-five students (mean age= 20.4, S.D.=3.1; females= 39, males=16) from the University of Milan-Bicocca took part in the study for course credits. Participants that took part in this experiment were different from the participants of the previous experiments. As in the previous experiments, the number of participants was determined a priori following the guidelines proposed in Brysbaert and Stevens (2018). None of the participants reported any visual or linguistic disorder. All the participants were Italian native speakers. Before their participation, they were informed of the experimental procedures and consented to take part in the experiment, which was approved by the local ethics committee.

4.1.2 Materials and design

The target conjugated verbs and the pseudo-verbs that we enrolled as materials were the same we used in Experiment 2. In addition to the 400 verbs and pseudo-verbs of Experiment 2, we also included a total of 180 filler stimuli consisting of: 45 time-unrelated existing nouns that contained an accent mark on the final syllable (such as *verità* “truth”); 45 time-unrelated existing morphologically complex nouns (such as *giornalista* “reporter”); 30 pseudo-nouns that resulted from the modification of time-unrelated existing nouns that contained an accent mark on their final syllable (such as *scolaripà,* from the noun *scolarità* “schooling”); 30 pseudo-nouns that were obtained by the modification of time-unrelated

morphologically complex nouns (such as *aupista,* obtained from the noun *autista* "driver"); 15 past pseudo-verbs that differed from the target pseudo-verbs for the fact that these latter included an orthographic change on the stem, while the filler pseudo-verbs included such change on the word ending (such as *viaggiaco* which resulted by the manipulation of the existing past-conjugated verb *viaggiavo* "I travelled"); 15 future pseudo-verbs that contained the manipulation on the ending (such as *viaggepò*, obtained by the manipulation of the existing future-conjugated verb *viaggerò* "I will travel"). Note that, in these latter two cases, the amendment in the endings de facto eliminates any time-related information from the stimulus.

We divided the 580 stimuli into two lists, in order to avoid the coexistence of verbs and pseudo-verbs that were obtained from the same stem [for instance, if list 1 contained the verb *cred-evo* ("I believed"), the pseudo-verb *crid-evo*, obtained from the manipulation of the same stem, appeared in list 2]. Each participant was presented with both lists in separate blocks. The order of presentation of the lists and the hands used to respond (A=words, L=pseudo-words first and vice versa) were counterbalanced between the blocks.

All the stimuli are openly available in the OSF repository https://osf.io/k4w7g/?view_only=df8ae2b101ed4392a1d5ef21d55f109c

4.1.3 Procedure

The procedure was precisely the same as Experiment 2.

4.2 Analyses and Results

A total number of 31900 observations were collected, matching the recommendation for a properly powered mixed-effects analysis of 1600-datapoints-per-condition (Brysbaert

and Stevens, 2018). All the participants successfully completed the experiment, with accuracy score >.85 for each of them. Filler stimuli were not included in the analysis.

We first ran a linear mixed-effects model with log-transformed response times as the dependent variable, a three-way interaction between tense, hand used and category of the stimuli as predictors, and items and subjects as random intercepts. Results showed that the interaction between tense, hand and category did not predict the response times (t=-1.9; p=.055).

We then simplified the model, running a linear mixed-effects model with log-transformed response times as the dependent variable, three two-way interactions, the first between the tense of the stimuli and the hand used to provide the response, the second between the tense and the category of the stimulus and the third between category and hand, as predictors, and subjects and items as random intercepts. Results showed that the interaction between tense and hand did not predict the response times (t=.73, p=.46). Contrarily both the interaction between tense and category (t=-2.6, p=.009) and between hand and category (t=4.9, p<.001) significantly predicted the response times. These results indicated that verbs received faster responses with respect to pseudo-verbs and that past tense stimuli were responded to faster than future stimuli (Figure 5).

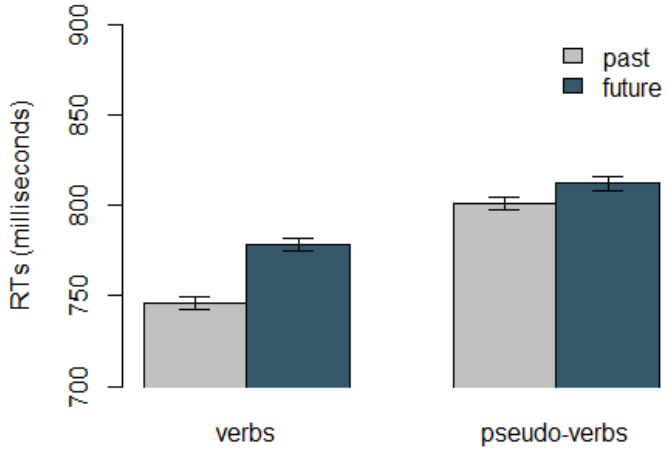

Figure 5. Barplot representing the means of the response times for verbs and pseudo-verbs when appeared at the past and future tense.

Moreover, verbs were responded to faster with the left hand and pseudo-verbs received faster responses with the right hand (Figure 6).

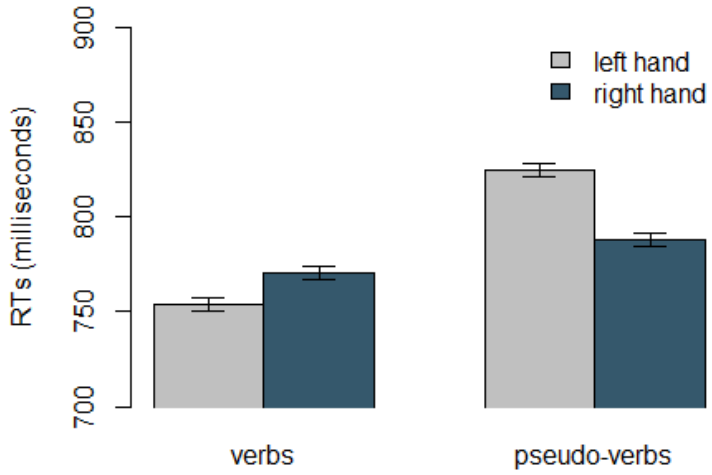

Figure 6. Barplot representing the means of the response times for verbs and pseudo-verbs when responded to with the left and right hand.

We observed the means of the response times split according to the category of the stimuli. Overall, we observed that verbs received faster responses with the left hand when they were conjugated both to the past and to the future; pseudo-verbs received faster responses with the right hand, independently of the tense of the stimuli (Table 6).

Table 6. Means of the response times (in milliseconds) with the Standard Error of the Means for verbs and pseudo-verbs conjugated to the past and future tense when responded to with the left and the right hand.

	Left hand	Right hand
Past verbs	722.3 (4.6 SEM)	750.6 (4.9 SEM)
Future verbs	772.1 (4.9 SEM)	782.7 (5.3 SEM)
Past pseudo-verbs	811.8 (5.1 SEM)	780.2 (4.7 SEM)
Future pseudo- verbs	816.2 (5.2 SEM)	779.4 (5.1 SEM)

To examine data concerning accuracy we performed the same statistical analysis. No significant effect of accuracy was observed.

4.3 Discussion

Experiment 3 was aimed at investigating whether past and future conjugated verbs and pseudo-verbs triggered spatial-temporal association effects in a task in which they were evaluated together with tense-unrelated filler stimuli. Testing whether the effect on verbs and pseudo-verbs was detected also when the task involved stimuli that are unrelated to the temporal dimension allowed us to evaluate whether the activation of the MTL observed in Experiment 2 is an automatic phenomenon, or whether reliable associations with the temporal aspect are necessary to its activation.

Results of this experiment showed that past and future conjugated verbs received faster responses with the left hand, while past and future conjugated pseudo-verbs received faster responses with the right hand. Moreover, the interaction between the hand used to provide the response and the category of the stimulus significantly predicted the response

times, suggesting a crucial role of the category of the stimuli rather than their tense Indeed, verbs were responded to faster with the left hand and pseudo-verbs received faster responses with the right hand. The findings of this study suggest that a spatial-temporal congruency effect does not emerge when verbs and pseudo-verbs are presented together with stimuli that belong to a different word class and that have no temporal reference.

These results are in line with previous studies (Santiago et al., 2007; Aguirre and Santiago, 2017; Sobbe et al., 2019; Ulrich and Maienborn, 2010; Ulrich et al., 2012) that reported the lack of the activation of the Mental Time Line when the task did not ask to evaluate the temporal dimension, but they contrast with the results from Experiment 2 of the present paper, showing a MTL activation in a lexical decision task. Taken together, these findings point to the importance of the composition of the item list in eliciting spatial-temporal association effects from non-lexical stimuli, over and above the administered task. In scenarios where the temporal information is less consistently related to linguistic elements (either because of the variety of used stimuli, or previous language experience) the effect tends not to emerge in behavioral data.

Concerning the interaction between the category of the stimuli and the hand used to respond, we hark back the interpretation of this pattern to the spatial-frequency association effect reported by Hutchinson and Louwerse (2014). According to this interpretation, high frequency words receive faster responses with the left hand, while low frequency words receive faster responses with the right hand. Now, considering that verbs are associated with frequency values, but pseudo-verbs do not, since they do not exist in the language, a striking unbalancing in frequency could have led to the pattern that we observed for verbs and pseudo-verbs. As for the previous experiment, this effect could be framed and interpreted within the ATOM theory (Walsh, 2003), according to which, beyond the time-

related dimension of the stimuli, participants activated a spatial representation of the existing *versus* non-existing category.

Hence, the present experiment showed that the Mental Time Line is not activated by the evaluation of a set of stimuli which do not refer homogeneously to time.

5 General discussion

The aim of the present study was two-fold. First, we wanted to explore whether sub-lexical strings, namely verb endings, carry conceptual information about time able to activate the Mental Time Line, a representational format according to which past-related events are associated with the left side of the mental space and future-related events with the right side space (for a review, see Bonato, Zorzi, & Umiltà, 2012). To test this first hypothesis, we created a set of stimuli that contained verbs and pseudo-verbs, namely non-lexical orthographic strings whose endings were the same as conjugated past (e.g., -avo) and future (e.g., -erò) verbs. We then asked first participants to perform a categorization task (Experiment 1), in which they had to indicate whether the stimulus presented was conjugated to the past or to the future using either the left or the right hand to provide the response. Results showed a facilitation effect when stimuli with past endings were responded to with the left hand and stimuli with future endings were responded to with the right hand rather than when the opposite response mapping was required. These results indicate that the spatial-temporal effect emerged for both existing conjugated verbs and non-existing pseudo-verbs. Since pseudo-verbs are not lexical elements and so they are not linked to any lexical representation, these findings demonstrate that the MTL can be activated by verb-endings, i.e., sub-lexical units.

The second aim concerned whether the spatial-temporal association effect emerged when the tense of the stimuli was not relevant to the task. We observed that the spatial-temporal congruency effect emerged also when time was not the relevant dimension at hand of the task, i.e. by employing a lexical decision paradigm (Experiment 2). However, evaluating verbs and pseudo-verbs together with time-unrelated stimuli (Experiment 3) showed that the activation of the MTL was crucially modulated by the variety in stimulus list.

The fact that phenomena linked to the Mental Time Line are observable also when the temporal dimension is not explicitly taken into consideration is extremely relevant to the discussion concerning the causes of the space–time congruency effect (von Sobbe et al., 2019). Indeed, if the spatial-temporal effect can be observed only when the task requires to consider the temporal dimension, the effect should be strictly limited to the performance of temporal placement in a particular situation (Santiago, Roman, and Ouellet, 2011). Yet, if the spatial-temporal association effect is observed also when performing tasks in which the temporal dimension is not relevant, as we found in Experiment 2, the results should be interpreted as an automatic activation of the Mental Time Line (Eikmeier, Alex-Ruf, Maienborn, Schreoter, & Ulrich, 2015; Núñez and Cooperrider, 2013). Our findings thus suggest that the spatial-temporal association effect, emerging also when the temporal dimension was not explicitly mentioned, may be related to an automatic activation of spatial codes. However, results from Experiment 3 suggest that the automatic activation we reported might be conditioned by the reliability of the temporal information conveyed by the stimuli. When the temporal cues in the employed stimuli are too varied or inconsistent, an effect of the MTL is not evident, thus questioning the full automaticity of the MTL activation. The results of this last experiment allow us to offer a more general explanation and interpretation of the spatial-association effect that we observed in relation to verb

endings and, more in general, to discuss the mechanisms that may underpin the MTL. Indeed, if we consider the results of the first two experiments of the present study, we might support the idea that the MTL is an automatic phenomenon in its absolute conception, but if we include in the picture the lack of the activation observed in the third experiment, we can conceive the MTL as a tool that comes into play to strategically process time-related entities. Hence, being a tool used to organize abstract knowledge into the more concrete domain of the spatial representation, it is activated only when a specific type of knowledge, precisely temporal knowledge, can be identified (albeit implicitly, as in experiment 2). For this reason, the presence of time-unrelated stimuli can undermine the ability to identify the type of knowledge that needs to be processed and hence the MTL, conceived as a strategic mechanism for the organization of knowledge, is not activated.

With respect to the literature about this topic, most of the previous studies did not find any spatial-temporal effect when the temporal information was not relevant to the task at hand (Santiago et al., 2007; Aguirre and Santiago, 2017; von Sobbe et al., 2019; Ulrich and Maienborn, 2010; Ulrich et al., 2012). Beyond the possible differences between previous experiments and the present ones already mentioned in the discussion of Experiment 2, another possible factor may have influenced their results, namely the underestimation of the fact that the concept of time is not univocal and monolithic. We mention here a major distinction between two common representations of time. The first concerns *deictic time* (D-time), which involves the present moment (now) as the reference point to derive the temporal categories of past and future (Núñez and Sweetser, 2006; Nunez and Cooperrider, 2013). The second is the so-called *sequence time* (S-time), which concerns the relation between two temporal events, with no necessary anchoring to the present moment (Núñez and Sweetser, 2006; Nunez and Cooperrider, 2013). This concept of time emerges from

adverbs like “after” and “before”, in which the temporal relation can be expressed in terms of earlier-than an external reference and later-than an external reference. Considering these frameworks, the present study involved stimuli that consistently belong to the first category, namely D-time, since the stimuli that we involved in our experiment refer to the past or to the future with the present moment as a reference point. The temporal information of the verbs “I will play” or “I played” is interpretable only in light of an internal reference (“now”) with respect to which the action of playing will occur and occurred. If the “now” changes location on the timeline, also past and future events would change their locations, being anchored to the present moment. Other studies, however, enrolled sets of stimuli that were not self-consistent in the kind of temporal concept that they expressed. For instance, if we consider the set of items reported by Torralbo and colleagues (2006), we notice that the temporal adverbs involved clearly refer both to D-time and S-time. For instance, some of the adverbs reported in the list are: *ayer* (“yesterday”), *mañana* (“tomorrow”), *recientemente* (“recently”), *próximamente* (“soon”), which refer to D-time; *anteriormente* (“previously”), *posteriormente* (“subsequently”) and *antes* (“before”), *después* (“after”), that refer to S-time. Santiago and colleagues (2007) and Aguirre and Santiago (2017) enrolled an analogous set of stimuli, while Oullet and colleagues (2011) adopted the same stimuli as Torralbo and colleagues (2006). This inhomogeneity could also have contributed to the weakening and disappearance of the spatial-temporal effect when the task was tense-irrelevant in these previous studies.

Finally, results of our study are informative not only of the conceptualization of time, but also of the linguistic units that can encode time-space-related information. Our findings demonstrate that sub-lexical strings, in particular affixes, provide not only grammatical information about verbal tense, but they rather encode conceptual information, which in

turn can activate spatial-temporal congruency effects irrespectively of the linguistic context in which they are embedded (i.e., verb or pseudo-verb). This contribution is relevant to both the line of studies that concerns word-processing and to the literature that concerns grounded effects.

Indeed, the fact that the verb-endings activate grounded effects also in pseudo-verbs is in contrast with morphological parsing models, postulating that during word processing only linguistic strings clearly parsable into stem and affixes are, in fact, decomposed (Roelofs, 1997; Taft, 1994; Rastle, Davis, & New 2004). According to these models, when analyzing the pseudo-verbs involved in the present paper no morphological parsing is expected to occur, since the pseudo-stems are non-existing strings and hence the whole string is, by definition, non-parsable. Being the pseudo-verbs not subjected to morphological parsing, the semantic information contained in the inflectional suffixes should not be extracted and no spatial-temporal effect should be activated in relation to it (Levelt, 1999). Our results provide evidence in contrast with this parsing view. A better theoretical framework to interpret our results is provided by distributed models (Stevens and Plaut, 2022). Indeed, these kinds of models do not involve any explicit representations for morphemes or words, but their architecture implies that simpler elements, such as graphemes or letter n-grams, are directly mapped onto a semantic layer. The NDL model (Baayen et al., 2011), an empirically validated model that is trained on examples of natural language use, offers a framework into which our results can be interpreted. The model involves that the morphological status of the past and future verb endings is not captured through an explicit representation unit for suffixes like *-avo* and *-erò*, but it rather emerges as strong connection links between the verb-endings as graphemic units and the corresponding temporal information of the past and future tense.

Incidentally, this perspective ideally explains the lack of MTL-like effects in previous studies and in our Experiment 3. Indeed, as we already discussed in the Introduction, the French past verb ending *-ais*, characterizing the first-person singular of the past tense and used in the past-related stimuli in Grasso et al. (2021), is also employed as a nominal suffix, typically to indicate geographic provenience (e.g., *Franç-ais*, "French"), and hence is overall not a reliable cue for temporal information. The NDL approach could also explain the lack of effect in Flumini and Santiago's (2013) lexical decision experiment as a by-product of the competition between graphemic cues. In fact, in this study a number of different endings was indicative of temporal information, ensuing a competition for the same semantic outcomes (past vs. future); as a result, during the experiment, these very same cues might end being less exploited by participants, in turn attenuating the overall space-time association effect. Finally, also in Experiment 3 of the present study, when the association between sub-lexical information and time-related information is made less reliable (as we added time-unrelated fillers), the spatial-temporal effect disappeared.

The fact that the semantic information carried by the verb-endings activated the MTL also rejects the idea that sub-lexical elements do not bring conceptual information (Roelofs, 1997; Levelt et al, 1999). For instance, according to the model by Levelt and colleagues (1999) morphological decomposition occurs at the lemma stage, in which morpho-syntactic characteristics are encoded: at the lemma stage, only information about the person they refer to, verb mode and tense are processed. In this framework, tense is intended as grammatical information only, with no reference to past and future as temporal concepts (see also the WEAVER network model by Roelofs, 1997). Our results are thus not compatible with this hypothesis, as we show that the sub-lexical elements that form the pseudo-words do encode enough conceptual information to activate a spatial-temporal congruency effect.

With respect to the literature on grounded effects, the fact that inflectional elements can trigger such a grounded phenomenon as the activation of the MTL is a new contribution in the field. Indeed, to our knowledge, there are only two studies that link grounded or embodied effects to sub-lexical elements (Connell and Lynott, 2011; Günther, Petilli, and Marelli, 2020). Connell and Lynott (2011) investigated the processing of novel complex words and showed, even though through explicit judgements, that embodied representation has an interactive role in conceptual processing. Günther and colleagues (2020) identified facilitatory effects of vision-based compositionality on the processing of both novel and existing compound words. In other words, the ease of combining vision-based representations of the constituents leads to a facilitation during compound processing. However, the evidence from these studies concerned compound words only, which significantly differ in lexical status from inflected words: in compounds both constituents can appear as free words, contrarily to inflected words such as *gioch-erò* (I will play), in which the ending *-erò* is consistently a - element (i.e., it is not a word on its own).

In conclusion, our findings add knowledge to the spatial-temporal association effect domain and to the semantic contribution of sub-lexical strings to both word processing and grounded phenomena, since we demonstrated that (i) the MTL can be activated by word endings, irrespective of the lexicality of the stimulus itself, and that (ii) the MTL is active also when not directly evaluating the temporal dimension of the stimuli, provided that the temporal information is reliable.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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