Time interaction with two spatial dimensions: from left/right to near/far

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Abstract

We explore time and space relationship according to two spatial coding: the left/right extension and the reachability of stimulus along a near/far dimension. Four experiments were carried out in which healthy participants performed the Time and Spatial Bisection tasks in near/far space, before and after a short or long tool-use training. Stimuli were prebisected horizontal lines of different temporal durations in which the midpoint was manipulated according to Muller-Lyer illusion. The perceptual illusory effects emerged in spatial but not temporal judgments. We revealed that temporal and spatial representations dynamically change accordingly with individual's action potentialities: temporal duration was perceived as shorter and the perceived line's midpoint was shifted to the left in far than in near space. Crucially, this dissociation disappeared following a *long* but not *short* tool-use training. Finally, we observed age-related difference in spatial attention which may be crucial in built the memory temporal standard to categorize durations.

Keywords: time estimation; spatial judgment; Muller-Lyer illusion; long and short tool-use; ageing.

Introduction

In everyday activities we commonly experience an intimate coupling between time and space. In this respect it was largely demonstrated that the stimulus spatial position, on the left or on the right side, influences time perception (see Bonato et al., 2012 for a review). More recently it was demonstrated that also the stimulus position in the depth dimension, near and far space, impacts time perception (Anelli et al., 2015).

As far as the influence of *left/right spatial coding* on time estimation, it was demonstrated that the duration of stimuli presented on the left is perceived shorter compared to stimuli presented on the right (Vallesi et al., 2008; Vicario et al., 2008; Frassinetti et al., 2009). These findings have contributed to formulate the hypothesis that humans represent time along an horizontal line (Mental Time Line) where temporal intervals are typically represented in ascending order from left to right (Santiago et al., 2007, 2010; Ishihara et al., 2008; Müller and Schwarz, 2008; Weger and Pratt, 2008; Magnani et al., 2011; Vallesi et al., 2011; Di Bono et al., 2012; Oliveri et al., 2013; Isham and Ekstrom, 2018).

Near/far spatial coding influences time perception too: stimuli presented in far space are perceived shorter in duration as compared to stimuli presented in near space (Anelli et al., 2015). The distinction between near and far space depends on the extent to which an action can be performed. (Rizzolatti et al., 1997; Berti and Frassinetti, 2000; Cardinali et al., 2009). Thus, near space is defined as the reachable space inside the arm's reaching distance and far space is defined as the unreachable space outside the reaching distance (Maravita and Iriki, 2004; Bartolo et al., 2014; de Vignemont and Iannetti, 2015).

A further evidence supporting the role of performing action *per se* or individual's action capability in mediating the distinction between near and far space is provided by the effects of tool-use which extends action capabilities (see, for reviews, Johnson-Frey, 2003, 2004; Maravita and Iriki, 2004; Witt, 2011; Reynaud et al., 2016; Biggio et al., 2017; Forsberg et al., 2019; Patanè et al., 2019). Indeed, tool-use allows to reach objects located in a far/unreachable space and consequently extends the reaching space's boundary (Berti and Frassinetti, 2000; Longo and Lourenco, 2006; Hunley et al., 2017; but see also D'Angelo et al., 2018; see, for review, Brozzoli et al., 2012; Martel et al., 2016).

The distinction between near and far space and its plasticity have been widely demonstrated in several behavioral studies adopting visuospatial tasks, such as the line bisection and landmark task which require to identify the subjective mid-point of a horizontal line (Bisiach et al., 1998; Lindbergh & Kieffaber, 2013; Patanè et al., 2016). In these tasks, when stimuli are presented in near space, healthy participants typically exhibit a leftward bias that gradually shifts rightward as the stimulus is moved further away (Bowers and Heilman, 1980; Jewell and McCourt, 2000; Longo and Lourenco, 2006; 2007). However, some studies adopting a line bisection task reported the opposite, that is a rightward bias in near space compared to far space (Bjoertomt et al., 2002; Varnava et al., 2002; Cowie and Hamil, 1998; Braun and Kirk, 1999; McCourt and Garlinghouse, 2000). What is of interest here is that when using a tool, that extend the near/reachable space up to the far/unreachable space (i.e., a long tool), a bias similar to that observed in near space emerged also in far space (Longo and Lourenco 2006). This is not true when a short tool is used that does not extend the action capability and does not allow to reach the far space (Patanè et al., 2017; Candini et al., 2019; Anelli et al., 2015; Bourgeois et al., 2014; Costantini et al., 2011; Farnè et al., 2005).

Furthermore, a relevant issue is that age influences the bias found in line bisection task. However, the nature of this effect is somewhat controversial: some studies have demonstrated an attenuated bias with age (Schmitz and Peigneux, 2011; Schmitz et al., 2013; Benwell et al., 2014; Learmonth et al., 2015; Friedrich et al., 2018), whereas other studies have put in evidence an accentuated bias with age (Harvey et al., 1995, 2000), or no effects of age (Learmonth et al., 2017). In a similar vein, a still debated question concerns the role of age in time estimation: temporal processing appears to be altered in healthy aging which is often associated with a faster passage of subjective time (Paraskevoudi et al., 2018; Turgeon et al., 2016; Rueda and Schmitter-Edgecombe, 2009; Perbal et al., 2002; Craik and Hay, 1999). For instance, Craik and Hay (1999) found that older participants perceived stimuli duration as shorter, compared to the veridical temporal duration, than younger participants. However, other studies found the opposite tendency in aging, that is to perceive longer stimuli duration compared to the veridical interval (Block et al., 1998; Turgeon et al., 2011). Thus, it remains unknown how ageing actually influences and determines the response bias observed either in spatial or temporal judgments.

Here, we concurrently investigate the relationship between time and two different spatial coding: the horizontal extension along a transversal axis (from left to right) and the depth dimension along a sagittal axis (from near/reachable to far/unreachable). Moreover, accordingly with several evidence demonstrating that age influences spatial and time perception, we expect a different performance between young and elderly participants in temporal estimation as a function of stimulus' spatial coding. To these aims, we study the effects on time perception of a perceptual illusion, altering the left/right spatial coding (Muller-Lyer illusion), and of the tool-use, modifying the boundary between near and far space.

Young and ageing healthy participants were submitted to two Time experiments and two Spatial experiments. In the **Time Bisection task**, participants estimated whether stimuli was “short” or “long” in duration, with respect to a previously acquired pair of references (1600 ms and 2400 ms). Stimuli consisted of horizontal prebisected line and were displayed according to the Brentano version of the Muller-Lyer illusion. This type of illusion uses three different arrows arranged in such a way that one half of the line is apparently expanded whereas the other half appears to be compressed (Coren et al., 1978; Weidner and Fink, 2007). We predicted that, if the spatial bias induced by the Brentano version of the Muller-Lyer illusion influences time perception, when the transector is perceived as nearer to left end of the line, time should be perceived as shorter, and when the transector is perceived as nearer to right end of the line, time should be perceived as longer. Furthermore, the effects of depth on time and its plasticity were assessed by presenting stimuli both in near and far spaces, before and after a long tool-use training. According with previous findings, time is expected to be perceived as shorter in the far compared to near space, before but not after a long tool-use training (Anelli et al., 2015; Petrizzo et al., 2021).

To verify the presence of illusory effects induced by the Muller-Lyer configuration, participants were submitted to the Spatial Bisection task, in which the same stimuli of the Time Bisection task were used, exception for stimulus' duration which was not manipulated and set at 2000 ms. Participants were required to judge which end of the pre-bisected line the transector was closer to.

Furthermore, two additional control experiments were also conducted in which the same Time Bisection task and Spatial Bisection task previously described were performed before and after a short tool-use training (Patanè et al., 2017; Candini et al., 2019; Anelli et al., 2015; Bourgeois et al., 2014; Costantini et al., 2011; Farnè et al., 2005).

We expect that testing the effect of Muller-Lyer illusion on time estimation will provide a critical contribution to understand how visual perception influences time processing. Moreover, changes in time estimation might be driven by the possibility to act in space, regardless of the perceived illusory spatial bias. If that is the case, we should find that the body proximity and the active long tool but not short tool-use training are effective to modulate time estimation.

Experiment 1: Time Bisection Task

Material and methods

Participants

Thirty-six right-handed neurologically healthy volunteers with normal or corrected-to-normal vision were recruited. The sample size was calculated by using G Power 3.1.7 hypothesizing an estimated effect size of $f=0.4$, and a power at 80% (Anelli et al., 2015). Eight-teen of them were elderly participants (6 males, mean $\pm$ sd age = 57.9 ± 6.9 years; mean $\pm$ sd education = 13 ± 4.6 years) and eight-teen were younger participants (5 males, mean $\pm$ sd age = 23.4 ± 3 years; mean $\pm$ sd education = 17 ± 1.7 years).

All participants were naive to the purpose of the research and provided written informed consent to participate in the study. The study which was approved by the local ethics committee (Department of Psychology, Bologna) and all procedures were in accordance with the ethical standards of the 2008 Helsinki Declaration.

Stimuli

Stimuli were black prebisected horizontal line displayed on a white screen positioned at 60 cm (near space) or 120 cm (far space) from the participant's eyes. In order to ensure that the retinal angle remained constant ($0.48^\circ \times 5.25^\circ$ VA) across viewing distances, the size of stimuli was adjusted (near space: 0.5 cm height and 5.5 cm length; far space: 1 cm height and 11 cm length). Each horizontal line was bisected by a black arrow (transector) and two more black arrows were presented at the line's ends, which could be oriented to the left or to the right side. Indeed, two different illusory conditions were presented: *Left expanded* (left sided outgoing fin/right sided ingoing fin) and *Right expanded* (left sided ingoing fin/right sided outgoing fin). Throughout the paper, the two types of illusory stimuli are distinguished with reference to the orientation of outgoing fins (left or right expanded side). The fin formed with the line a 45° (ingoing; $> <$) or a 315° (outgoing; $< >$) angle. Across trials, the stimuli varied according to: 1) the 2 stimulus orientations (left/right); 2) the 3 positions at which the horizontal line was bisected (shift to the left: -0.2° ; true center: 0.0° ; shift to the right: $+0.2^\circ$) and 3) the 5 stimulus's durations (1600, 1800, 2000, 2200, or 2400 ms; Figure 1) for a total of 30 stimuli combinations. Each stimulus was repeated six times, thus obtaining a total of 360 trials. In order to reduce the effect of fatigue on participant's performance, three different blocks of 60 trials were presented for each condition: 180 in the near space, and 180 in the far space.

Each trial began with the presentation of a fixation cross displayed on a white background for 500 ms, after which the stimulus was displayed for one of the five temporal durations

(1600, 1800, 2000, 2200, 2400 ms) and, then replaced by a white background which remained visible until a verbal response was made. After the response, the subsequent trial was presented following a random inter-trial interval (range 600–1000 ms; see Figure 2). Stimuli were centrally displayed on a 15” LCD monitor (resolution 1366 x 768 pixels) and were presented by using the E-Prime 2.0 software package (Psychology Software Tool ©1996-2012, USA).

Figure 1 – Example of the stimuli adopted in the experimental tasks according to the left/right side orientation, and the transector’ positions (a: -0.2° ; b: 0.0° ; c: $+0.2^\circ$). The vertical dot lines represent the true center of each prebisected line.

Procedure

Participants were comfortably seated directly in front of the monitor screen and were asked to rest their hands on their thighs. The experimenter ensured that the subject’s body position remained constant during the whole experiment.

The Time Bisection task consisted of the verbal classification of a series of prebisected lines that were displayed for different durations at the center of the computer screen. We adopted a two alternative forced choice paradigm in which participants have to judge whether the duration of each line was “short” or “long” with respect to previously acquired pair of reference durations (1600 ms and 2400 ms). In the practice session, a

total of eight trials were randomly presented and participants had to classify four intervals of 1600 ms as “short”, and four intervals of 2400 ms as “long”. Feedback was given on accuracy only for these eight practice trials. All participants reached at least 80% of accuracy with no more than two practice sessions. Then, they were submitted to the experimental task in which all the possible prebisected lines were randomly displayed. Participants were instructed to make their best guess if they were unsure, and to respond as accurately and as quickly as possible. No feedback was given in the experimental blocks.

The experimenter seated behind participants (at least 1.5 m) and recorded their verbal responses by pressing one of two keys on a wireless mouse (left for “short”/right for “long”). Each block of the time bisection task took approximately six minutes to complete.

The Time Bisection task was performed in two experimental conditions: in near space (60 cm from the computer screen) and in far space (120 cm from the computer screen), presented in separate blocks, counterbalanced across participants. The task was repeated twice, in the same order, before and after a tool-use session.

Figure 2 – Example of the experimental paradigm and sequence of events during each trial for the Time Bisection task. In the Time Bisection Task, participants were asked to judge whether the duration of each stimulus was “short” or “long” with respect to pair of short (1600 ms) and long (2400 ms) reference durations.

Tool-use session

During the tool-use training, the participant stood at the short side of a rectangular table. The experimenter randomly placed on the table a series of colored poker chips (red, green, yellow, white and black) outside the reaching space, at a distance of ≈ 100 cm from the participant's trunk. The chips were presented in the participants' midsagittal axis (0°), or at 10° and 20° to the left and to the right of the central position (-10° , -20° , $+10^\circ$, $+20^\circ$). Each participant performed about a total of 100 reaching movements in order to bring the objects close to their body with no time constraint. During the tool-use session, participants had to use a 70 cm-long rake with their right hand. The tool-use training lasted 15 minutes.

Data Analysis

In our paradigm, the bisection point is the estimated temporal value (expressed in ms) for which participants would respond “long” or “short” with equal probability. To estimate the bisection point, we first computed the percentage of “long” responses for each interval duration (1600, 1800, 2000, 2200, 2400 ms), and then cumulative Gaussian functions were fitted to the percentage of “long” responses across different stimulus durations using a logistic regression. The point at which the psychometric function cuts the 50% of “long” responses indicates the which means the duration at which a participant is equally likely to classify the stimuli as short or long (point of subjective equality, PSE). For each participant, the PSE was separately calculated for each type of illusion (left/right orientation) and transector position (-0.2° ; 0.0° ; $+0.2^{\circ}$), in each of the four conditions (pre tool-use/near space; pre tool-use/far space; post tool-use/near space; post tool-use/far space). Bisection points below 2000 ms reflect duration overestimation (i.e., durations are perceived longer than they actually are), whereas bisection points above 2000 ms reflect duration underestimation (i.e., durations are perceived shorter than they actually are). An increase of “longer” responses after tool-use session, as compared to pre-tool session, induces a decreased PSE, reflecting that durations are perceived being longer with respect to before tool-use session. Conversely, an increase of “short” responses after tool-use session induces an increased PSE, reflecting that durations are perceived shorter. Thus, the PSE allows us to observe whether tool-use session induced a temporal judgment bias towards either an underestimation or an overestimation of durations in near and far spaces.

Statistical analysis

The Kolmogorov–Smirnov test was conducted to verify whether our dataset was normally distributed or not. Since we did not obtain significant results ($p > .05$), we assumed the dataset was not significantly different from a normal distribution. First of all, in order to explore the

effect of temporal duration on participant's time estimation judgment, an analysis of variance (ANOVA) was conducted on the percentage of "long" responses recorded with Interval (1600, 1800, 2000, 2200, 2400 ms) as within-subject variable.

Secondly, in order to explore the effect of a tool-use training on the temporal task, an ANOVA was conducted on mean PSE value with Group (Young and Ageing participants) as between-subject variable, and Session (Pre- and Post-tool), Condition (Near and Far space), Orientation (Left and Right), and Transector (-0.2° ; 0.0° ; $+0.2^\circ$) as within-subject variables. When necessary, post-hoc analyses were conducted by using the Newman-Keuls's correction. The magnitude of effect size was expressed by partial eta squared (η_p^2).

Results of Experiment 1

The effect of time interval

The variable **Interval** was significant [$F(4,140)=470.2$; $p<.0001$; $\eta_p^2=.93$]: post hoc analyses revealed that all temporal durations differ each other revealing an increase of percentage of long response according to the increase of temporal durations (1600=15%; 1800=33%; 2000=55%; 2200=75%; 2400=86%; $p<.0001$ for all comparisons; see Figure 3a).

The effect of Muller-Lyer illusion and tool-use on temporal estimation

The ANOVA conducted on the PSE revealed a significant effect for the variable **Group** [$F(1,34)=3.19$; $p=0.028$; $\eta_p^2=.13$]: an underestimation of temporal interval was found in elderly (mean $\pm$ SEM 2019 $\pm$ 19.0) compared to younger participants (1948 $\pm$ 17.7; see Figure 3b). Crucially, the interaction **Session x Condition** [$F(1,34)=5.69$; $p=0.02$; $\eta_p^2=.14$] was significant. In the pre-tool session, temporal durations are perceived shorter (i.e., participants underestimated temporal interval) when stimuli were presented in far (2075 $\pm$ 59.6) compared to near condition (1954 $\pm$ 16.5; $p=.045$). By contrast, no such as effect was observed in the post-tool session between near and far conditions (1975 $\pm$ 27.9 vs. 1933 $\pm$ 21.7; $p=.66$).

Interestingly, when pre- and post-tool sessions were directly compared, a significant reduction of time underestimation emerged comparing far conditions ($p=.03$), whereas no significant differences emerged comparing near conditions ($p=.66$; see Figure 3c). No significant interaction for the factor Group and other variables was found (all p s > .05).

Insert Figure 3 about here

Figure 3 – **Participants' performance at Time Bisection task.** The percentage of long response as a function of duration interval (a). The point of subjective equality judgments (PSE) expressed as a function of Group (b). The PSE expressed as a function of tool-use session (pre and post) and conditions (near and far) (c). Error bars indicate standard error of means (SEM). Asterisks indicate significant differences.

Interim discussion of Experiment 1

First of all, time intervals were classified consistently with their effective durations, since the percentage of long response increased as the interval to be timed increased. Second, age

influences time estimation: elderly participants perceived temporal durations as shorter compared to young participants. Third, considering the depth dimension along the sagittal axis, our results highlight how temporal estimation is modulated by the space where the temporal stimulus is presented: temporal durations presented in far space are perceived shorter as compared to those presented in near space. This dissociation disappears following a tool-use session, in which participants actively perform a series of consecutive movements to reach objects located in a far and unreachable space by means of a long rake. Indeed, after tool-training, temporal stimuli presented in far space are processed as if they occurred in near space, demonstrating the role of action in “remapping of time”. Crucially, after an equivalent tool-use training but with a short rake, this effect was not observed (see Experiment 3 in Supplementary materials). Indeed, temporal durations presented in far space are perceived shorter as compared to those presented in near space in the pre-training session, and this dissociation was still present after the short tool-use training). Finally, we found that the Muller-Lyer illusion, which alters the left/right coding did not affect temporal estimation. . This last result can be explained in two different ways. First, the near/far space, coded by action possibilities, is more relevant for time estimation than the left/right spatial coding. . Secondly, participants could have not experienced the Muller-Lyer illusion at all . To rule out this last possibility, we assessed the occurrence of Muller-Lyer illusion by using a Spatial Bisection task. We used the same stimuli of Experiment 1 but, this time, participants had to judge which end of the line (“left” or “right”) the transector was closer to (Weidner and Fink, 2007).

Experiment 2: Spatial Bisection Task

The experimental procedure of the Spatial Bisection task was similar to the Time Bisection task, with the following exceptions.

Stimuli

Stimuli were black prebisected horizontal line displayed on a white screen positioned at 60 cm (near space) or 120 cm (far space) from the participant's eyes (see Figure 1). In the Spatial Bisection task, stimulus duration was fixed at 2000 ms. According to the 2 illusory conditions adopted (Left and Right expanded) and the 3 transector positions (-0.2° ; 0.0° ; $+0.2^\circ$), six different prebisected lines were obtained. Each stimulus was presented six times in a random order, yielding a total of 72 trials (36 in the near space, and 36 in the far space). Each trial began with the presentation of a fixation cross lasting 500 ms, then the stimulus was displayed for 2000 ms, and replaced by a white background, which remained visible until a response was made (see Figure 4).

Procedure

The Spatial Bisection task was performed in two experimental conditions, in near and far space, which were presented in separate blocks counterbalanced across participants.

The task was repeated twice, in the same order, before and after a tool-use session.

We adopted a left/right alternative forced choice paradigm in which participants have to judge which end of the line the transector was closer to. On each trial, participants were asked to verbally classify each prebisected line as “left” if the transector was perceived as being closer to the left end of the line, and as “right” if they perceived it to be closer to the right end.

A practice session was administered before the experimental task. In this practice session participants had to classify four prebisected lines at -0.2° as “left”, and four prebisected lines at $+0.2^\circ$ as “right,” all randomly presented. Participants received feedback only in these eight practice trials, which was repeated until they had reached at least 80% of accuracy. Then, they were submitted to the experimental task in which all the possible six prebisected lines were randomly displayed. Participants were instructed to make their best

guess if they were unsure, and to respond as accurately and as quickly as possible. No feedback was given in the experimental blocks.

The experimenter seated behind participants (at least 1.5 m) and recorded participants' verbal responses by pressing one of two keys on a wireless mouse (left/right). Each block of the Spatial Bisection task took approximately five minutes to complete.

Figure 4 – Example of the experimental paradigm and sequence of events during each trial for the Spatial Bisection task. Participants had to verbally classify each stimulus as “left” if the transector was perceived as being closer to the left end of the line, and as “right” if they perceived it to be closer to the right end.

Data Analysis

For each participant, to obtain an objective measure of the perceived line midpoint, we calculated the proportion of “right” responses (i.e., when subjects judged the transector as being at the right of the true center) in each of the four conditions (pre tool-use/near space; pre tool-use/far space; post tool-use/near space; post tool-use/far space). As expected in line with the visual illusion, participants typically fail to correctly judge the

midpoint of the line because half of the line appears shorter or longer than the real one with the ingoing fins ($> <$) and outgoing fins ($< >$), respectively (Ro and Rafal, 1996; Vallar et al., 2000; Daini et al., 2002).

An increase of “right” responses after tool-use session, as compared to pre-tool session, induces a relative shift toward the left of the perceived midline. On the contrary, an increase of “left” responses after tool-use session induces a relative shift to the right.

Results of Experiment 2

The effect of Muller-Lyer illusion and tool-use on spatial estimation

In order to explore the effect of a tool-use training on the spatial task, an Analysis of Variance (ANOVA) was conducted on the percentage of “right” responses recorded in each condition with Group (Young and Ageing participants) as between-subject variable, and Session (Pre- and Post-tool), Condition (Near and Far space), Orientation (Left and Right) and Transector (-0.2° ; 0.0° ; $+0.2^\circ$) as within-subject variables.

The analysis revealed a significant effect for the variable **Group** [$F(1,34)=6.55$; $p=0.02$; $\eta^2_p=.16$]: younger participants perceived the transector as closer to the left end of the line (mean $\pm$ SEM $48\%\pm 0.018$) compared to the elderly adults ($51\%\pm 0.013$; see Figure 5a). Furthermore, confirming the Muller-Lyer illusion’ effect, the interaction **Orientation x Transector** [$F(2,70)=10.9$; $p<.0001$; $\eta^2_p=.23$] was also significant. Post-hoc comparisons revealed that for right-side and left-side oriented stimuli, the difference in judging the transector position was at 0.0° . Participants judged the transector as closer to the right end of the line when it was at $+0.2^\circ$ ($98\%\pm 0.009$) and at 0.0° ($98\%\pm 0.012$) compared to -0.2° ($84\%\pm 0.036$; $p<.0001$). Conversely, for left-side oriented stimuli, an increase in right responses was found when the transector was at $+0.2^\circ$ ($14\%\pm 0.028$) compared to 0.0° ($2\%\pm 0.008$; $p<.0001$) and at -0.2° ($2\%\pm 0.008$; $p<.0001$). Both these significant effects confirmed that participants’ responses were affected by the direction of the illusion: right

side oriented lines induce the opposite effect, that is a shift of the midpoint toward the right whereas left side oriented lines induce a shift of the midpoint (transector) toward the left. (see Figure 5b).

Crucially, the interaction **Session x Condition** [$F(1,34)=3.98$; $p=0.05$; $\eta^2_p=.10$] was significant. In the *pre-tool session*, an increase in right response was found in near ($50\%\pm0.006$) compared to far condition ($48\%\pm0.009$; $p=.048$). By contrast, no such as effect was observed in the *post-tool session* (near space = $50\%\pm0.007$ vs. far space = $50\%\pm0.008$, $p=.89$). More relevant for the purpose of the study, when pre- and post-training sessions were directly compared, no differences emerged when near conditions were considered ($p=.91$), whereas following the tool-use session a significant increase in right response was found in far conditions ($p=.046$; see Figure 5c). No significant interaction for the factor Group and other variables was found (all $ps > .05$).

Figure 5 – Participants' performance at Spatial Bisection task. Midpoint values expressed as percentage (%) of right response as a function of Group (a). Percentage of right response expressed as a function of Muller-Lyer illusion (b), conditions (near and

far) and the tool-use session (pre and post) (c). Error bars indicate SEM. Asterisks indicate significant differences.

Interim discussion of Spatial Bisection task

Results of Spatial Bisection task put in evidence the effect of Muller-Lyer illusion on the perception of lines' midpoint. In fact, *right oriented stimulus* results in a shift of the midpoint toward the right. By contrast, *left oriented stimulus* results in a shift of the midpoint toward the left. This result perfectly fits with the the well-known effects of the Muller-Lyer illusion (Restle & Decker, 1977; Weidner & Fink, 2007). Moreover, age influenced the strength of the illusion: elderly participants showed a stronger rightward shift in the perceived line midpoint as compared to young participants. More interestingly for the current study, considering the depth dimension along the sagittal axis, our results demonstrate that the spatial judgment is also influenced by the stimulus' position in near or far space: a leftward shift in the perceived line's midpoint emerged in far as compared to near space. Furthermore, after a long tool-training, this dissociation disappears: when participants judged the midpoint of the line no difference was found between stimuli presented in near and far space. Importantly, this effect was not found after a training with a short tool (see Experiment 4 in Supplementary materials).. Indeed, the leftward shift in the perceived line's midpoint reported in far as compared to near space was still present before and after the short tool-use training. Thus, the lack of an effect of the Muller-Lyer illusion on time perception in Experiment 1 (Time Bisection task) is not explained by the fact that participants did not perceive the illusion. Rather, these results suggest that time is spatially organized, specifically when the space is encoded as a "working space" on which to act.

General

Discussion

The main purpose of this study was to explore the interaction between left/right and near/far spatial coding in temporal estimation, and their functional relationship. To address this, in

Time Bisection task stimuli were manipulated both along the transversal left-right axis, according with the Muller-Lyer illusion, and along the sagittal axis, by presenting stimuli in reachable/near and unreachable/far space.

The first relevant result is the influence of near/far spatial coding on temporal estimation. Before tool-use training, there was a clear dissociation between near and far spaces : temporal durations are perceived shorter when stimuli are presented in far as compared to near space. In order to explain this finding, we hypothesize that temporal duration of stimuli presented close to the body (i.e., near space) was perceived as slower and prolonged because of the influence of action preparation on time perception. Curiously, experts in motor performance, such as tennis and football players, usually report the feeling of the ball ‘slowing-down’ just before hitting it, and comment that they ‘see’ the ball more clearly before striking it (Murphy and White, 1978; Hagura et al., 2012). This implies that the subjective passage of time may be influenced by action, especially when participants performed movements close to one’s own body. Supporting this evidence, in a temporal judgment task, Hagura and colleagues (2012) found that stimuli were significantly overestimated (i.e., higher PSE values) when participants prepared for action compared with a control condition in which they had to detect visual stimuli. These results confirmed the claim that during motor preparation participants perceived the visual stimulus to have a longer duration. Then, a possible interpretation is that to accurately perform movements, the optimal strategy for the brain is to enhance detection of any environmental changes before motor execution, and that this leads to perception of slowing down time.

Interestingly, we demonstrated that the tool-use training eliminates the dissociation between near and far spaces in time estimation. disappeared, reporting the so-called *remapping of time*. This finding is in line with a previous study on young healthy participants (Anelli et al., 2015), and corroborates the idea that time is a physical dimension which interacts with reachability and individual’s action potentialities in space.

Supporting this hypothesis, a similar dissociation between near and far space, and a remap of far as near space after the long tool-use training, were also found in the Spatial Bisection task. Taken together, our findings converged to the idea that temporal and spatial representations dynamically change accordingly with individual's action potentialities. Coherently with this interpretation, following the short tool-use training no changes was observed either when temporal or spatial judgments were provided in time and spatial bisection tasks, respectively. This evidence is in line with several studies demonstrated that a short tool-use does not expand one's action capability (Patanè et al., 2017; Candini et al., 2019; Anelli et al., 2015; Bourgeois et al., 2014; Costantini et al., 2011; Farnè et al., 2005). The second finding concerns that, the illusory effect due to Muller-Lyer configuration in the Spatial Bisection task, does not influence Time Bisection. The Muller-Lyer illusion on the spatial judgement is not surprising since it is a visual perceptual illusion, as suggested by previous studies adopting a line bisection task. Neuroimaging studies demonstrated that occipital extrastriate cortex, especially the lateral occipital cortex, is associated with the strength of the Muller-Lyer's illusion (Weidner and Fink, 2007). This is coherent with several neuropsychological evidence indicating that the lack of experiencing the illusion in patients with visual deficit (hemianopia) correlates with the degree of damage in occipital regions (Vallar et al., 2000; Vuilleumier et al. 2001; Daini et al., 2002). Overall, the novelty of our findings is that there is not an influence of visual illusion inducing a spatial bias on time perception, rather the interaction between time and space is grounded into the concept of "working space" or "space for goal-directed action" (de Vignemont and Iannetti, 2015). A further critical result for this study concerns the influence of age on time and space processing. In Temporal Bisection task, young participants perceived temporal duration as longer compared to elderly participants, and in the Spatial Bisection task they showed a leftward bias. Coherently with the hypothesis that time is spatially represented, this bias due to a leftward shift of spatial attention (Friedrich et al., 2018), may influence time perception,

inducing a shorter reference-time-interval stored in memory in young than in elderly participants. Consequently, when young people compare interval duration with the reference time in memory, they overestimate the duration of stimuli. On the other side, in elderly people, who do not show the leftward bias, the reference-time-interval stored in memory is longer than in young, then they underestimate the stimuli duration. These data could suggest that individual differences in spatial attention may play a role in the construction of the memory temporal standard by which durations are categorized. Our results are in line with previous works on temporal processing which demonstrated that the underestimation bias found in temporal judgment in elderly people is due to a deceleration of the internal clock speed (Craig and Hay, 1999; Perbal et al., 2002). For instance, Craig and Hay (1999) argued that the pacemaker of elderly participants emits lower rate pulses that contribute to slowing-down the internal clock. This interpretation well fits with the common feeling that the sense of passage of time being fast in aging. At physiological level, the age-related changes observed in temporal estimation may be explained considering the functional role of dopamine in timing. Indeed, this neurotransmitter is well known for contributing to internal pace-making mechanism. In this respect, clock speed seems to be related to functioning of the frontal-nigrostriatal dopamine pathway: when a temporal stimulus begins, the substantia nigra responds by a dopamine release towards the striatum (Matell and Meck, 2004; see for review also Paton and Buonomano, 2018). Thus, age-associated changes in frontal brain regions and a gradual depletion of striatal dopamine could, at least partially, account for the alteration observed in time estimation in elderly participants (Meck et al., 2006). In conclusion, our results provide further support to the existence of a close relationship between time and space which is mainly driven by the closeness of the stimulus to the body. This finding reveals the highly flexible and plastic nature of time representation which could be for human an optimal strategy to enhance detection of sensory information in the

environment to accurately tune both spatial and temporal information during everyday activities.

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