As time goes by: SMA neuromodulation and time perception while watching moving images with different editing styles. A tDCS study

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Submitted to Journal:
Frontiers in Human Neuroscience

Specialty Section:
Cognitive Neuroscience

Article type:
Original Research Article

Manuscript ID:
1595599

Received on:
18 Mar 2025

Journal website link:
www.frontiersin.org

Scope Statement

The study aligns with the scope of the special issue "Neurocinematics: How the Brain Perceives Audiovisuals" by investigating the neural mechanisms underlying time perception in film viewing. Using a neurofilmological approach that integrates film studies, cognitive psychology, and neuroscience, we examined how cinematographic editing styles influence temporal judgments, with a specific focus on the supplementary motor area (SMA). By employing transcranial direct current stimulation (tDCS) and behavioral measures, our findings provide novel insights into the role of the motor system in shaping the viewer's experience of cinematic time. This interdisciplinary contribution advances the emerging field of neurocinematics and enhances our understanding of audiovisual perception.

Conflict of interest statement

The authors declare a potential conflict of interest and state it below

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision

Credit Author Statement

Adriano Daloia: Project administration, Resources, Supervision, Writing – review & editing. **Alessandro Antonietti**: Supervision, Writing – review & editing. **Alice Cancer**: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ruggero Eugeni**: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Stefania Balzarotti**: Methodology, Supervision, Writing – review & editing.

Keywords

Time Perception, Neuromodulation, tDCS, SMA, moving images, Editing style, Neurofilmology

Abstract

Word count: 190

In the context of the neurofilmological approachwhich integrates film studies, cognitive psychology, and neurosciencethe present study explored how cinematographic editing influences the viewer's perception of time. Previous behavioural research has shown that editing density affects temporal judgments. To investigate the neural mechanisms underlying this relationship, we examined the role of the motor system activity, specifically the supplementary motor area (SMA), in time perception when exposed to moving images with different cinematographic editing styles. Fortyeight university students were assigned to one of three tDCS conditions (anodal, cathodal, or sham). They viewed nine video clips with different editing styles (master shot, slow-paced, fast-paced) originally created for research. Participants rated perceived duration, time passage, action speed, and emotional engagement, while tDCS was applied for 20 minutes targeting the SMA. Results revealed that SMA excitability modulation affected duration estimates, time passage, and action speed judgments by interacting with the editing style of the clips. These findings highlight the importance of SMA in modulating time perception during film viewing. Furthermore, they provide valuable insights into the neural mechanisms that shape the viewer's perception of film time as an integral part of experiencing movement in cinema.

Funding information

PRIN 2017-2019 (National Interest Research Projects - ITALY) Perception, Performativity and Cognitive Sciences (grant number: 2015TM24JS–SH4).

Funding statement

The author(s) declare that financial support was received for the research and/or publication of this article.

Ethics statements

Studies involving animal subjects

Generated Statement: No animal studies are presented in this manuscript.

Studies involving human subjects

Generated Statement: The studies involving humans were approved by Ethics Committee of the Catholic University of the Sacred Heart in Milan, Italy . The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Inclusion of identifiable human data

Generated Statement: No potentially identifiable images or data are presented in this study.

Data availability statement

Generated Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Generative AI disclosure

The author(s) verify and take full responsibility for the use of generative AI in the preparation of this manuscript. Generative AI was used

linguistic revision

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Keywords: Time perception, neuromodulation, tDCS, SMA, moving images, editing style, neurofilmology

Abstract

In the context of the neurofilmological approach – which integrates film studies, cognitive psychology, and neuroscience – the present study explored how cinematographic editing influences the viewer's perception of time. Previous behavioural research has shown that editing density affects temporal judgments. To investigate the neural mechanisms underlying this relationship, we examined the role of the motor system activity, specifically the supplementary motor area (SMA), in time perception when exposed to moving images with different cinematographic editing styles. Forty-eight university students were assigned to one of three tDCS conditions (anodal, cathodal, or sham). They viewed nine video clips with different editing styles (master shot, slow-paced, fast-paced) originally created for research. Participants rated perceived duration, time passage, action speed, and emotional engagement, while tDCS was applied for 20 minutes targeting the SMA. Results revealed that SMA excitability modulation affected duration estimates, time passage, and action speed judgments by interacting with the editing style of the clips. These findings highlight the importance of SMA in modulating time perception during film viewing. Furthermore, they provide valuable insights into the neural mechanisms that shape the viewer's perception of film time as an integral part of experiencing movement in cinema.

1 Introduction

The subjective experience of time remains a complex and elusive concept in cognitive psychology research and has been at the centre of lively scientific debate in recent years (see Allman et al., 2014; Block and Gruber, 2014; Matthews and Meck, 2016; Thönes and Stocker, 2019). The mental representation of time is a multifaceted concept that encompasses processes such as temporal information processing (simultaneity, succession of events), the perception of temporal extension (duration), and the experience of time passage (the subjective feeling that time passes more quickly or slowly) (Thönes and Stocker, 2019). One of the most prominent models to account for subjective timing is the Scalar Expectancy Theory (SET) (Gibbon et al., 1984), according to which time perception relies on an internal clock, in which a pacemaker generates pulses that are temporarily accumulated and stored in working memory. The accumulated pulses, which form the basis of time estimation, are then compared to a reference memory, which holds past experiences of accumulated pulses, allowing for a cognitive representation of time. A decision process ultimately determines the appropriate temporal response based on this comparison.

The pacemaker-accumulator system is not merely a passive timer, but it actively contributes to behavioural state transitions (Killeen and Fetterman, 1988). Indeed, timing processing is the basis of anticipatory mechanisms and expectations of future occurrences. Humans, as well as animals, anticipate the occurrence of predictable future events through timing their own actions. From a behaviouralist perspective, the principle of anticipatory adaptation can be interpreted as an instance of temporal learning, as the sensitivity to the stable delay between the conditional and unconditional stimuli in Pavlovian conditioning is the mechanism that trigger the response (Ohyama et al., 2003). As a consequence, engaging in actions in response to temporal expectances, or even the mere mental representation of those actions, can influence the representation of time (Killeen and Fetterman, 1988).

The theoretical and empirical interaction between time experience and action has been explored by a multidisciplinary field of research that emphasizes the embodied nature of time perception (Altschuler and Sigrist, 2016; Coull et al., 2016; Meck and Ivry, 2016). Findings by Press and colleagues (2014) showed that the duration of a sensory stimulation (i.e., tactile vibration) was dilated by the concurrent action performance of a movement, as compared to being at rest. Moreover, several studies demonstrated that not only action execution, but also third-person observation of movements and actions can play a role in distorting or enhancing subjective time (Vatakis et al., 2014). Several findings have shown that a distortion of perceived duration of visual stimuli can be induced by observed movement (for a review, see De Kock et al., 2021). An example of that is the subjective time dilation (Tomassini et al., 2011) that is induced by an object moving towards an observer, as compared to a static object (Van Wassenhove et al., 2008). Similarly, a higher density of events caused by greater stimulus velocity also leads to time dilation compared to a slower-moving stimulus (Kanai et al., 2006). Not only actual movement affects time perception, but also implied or apparent movement was found to have similar enhancing effect. Nather and Bueno (2011, 2012) showed that perceived durations of observations for pictures and sculptures representing implied body motions (i.e., stills of dance movements) were longer as compared to stimuli representing unmoving figures. Even the exposure to abstract paintings that represented human motion was able to induce similar subjective time modulations (Nather et al., 2014). Such lengthening effect has been attributed to different internal clock processes for moving versus static stimuli, driven by the recruitment of additional mechanisms linked to embodiment (e.g., procedural memory). Particularly, movement observation induces temporal visuomotor representations based on the motor knowledge of human actions, that leads to an internal clock acceleration (Nather and Bueno, 2011).

Interestingly, even the intensity of the represented movement plays a role in affecting the duration estimates. Nather and Bueno (2011) indeed found that observing whole bodies representing lower movement intensities tend to be underestimated, while those with the highest movement intensity to be overestimated. The stimuli with intermediate movement intensity were the ones that led to the most accurate duration judgements. These results are consistent with the evidence of the common high precision of human interaction with moving objects. Most social interactions in daily life (e.g., a handshake) require accurate temporal judgments about position changes over time in order to execute a motor output at the right moment (Gavazzi et al., 2013).

In the attempt to disentangle the contribution of a specific visuomotor mechanism relying on the motor representation of human actions from the confounding influence of perceptive biases in duration judgments of moving objects, Gavazzi and colleagues (2013) compared visual stimuli with biological versus nonbiological kinematic properties. The authors found that the temporal estimation accuracy is improved by the correspondence between the stimulus' kinematics and the observer's motor competencies (i.e., participants were asked to replicate the duration of a dot moving in the vertical plane by moving their right arm along the vertical plane). These results suggest that the temporal mechanism of visual motion relies on a temporal visuomotor representation shaped by motor knowledge of human actions. This interpretation is consistent with the consolidated role of the mirror neuron system in action observation (Gallese et al., 1996; Rizzolatti et al., 1996), which supports the notion that the motor brain areas responsible for the execution of a specific action are activated during observation of the same action performed by another individual.

Neuroscientific research has indeed confirmed the motor system involvement in time perception processes (Macar and Vidal, 2004). Although temporal perception and estimation tasks involve a distributed brain network including cortical and ventral structures (e.g., the basal ganglia, the cerebellum, premotor, parietal and dorsolateral prefrontal cortices) (Meck, 2006; Paton and Buonomano, 2018; Nani et al., 2019), neuroimaging studies have highlighted a key role of the Supplementary Motor Area (SMA) in temporal processing (Macar and Vidal, 2004; Macar et al., 2006; Wiener et al., 2010; Coull et al., 2011, 2016; Schwartze et al., 2012). Specifically, the activation of this area, which is typically involved in motor control and planning (Tanji, 2001; Nachev et al., 2008), is proportional to the duration of the visually presented temporal stimulus (Coull et al., 2015), regardless of its association with a motor response planning task. Further evidence on the role of SMA in temporal processing tasks can be found in the neuroscience literature. It has been observed that temporal ability is impaired in patients with SMA lesions (Halsband et al., 1993). Furthermore, functional magnetic resonance imaging (fMRI) studies have detected SMA involvement during temporal perception tasks (see Coull, 2004). Electrophysiological studies based on event-related potentials (ERPs) have recorded an increase in SMA activation proportional to the estimated temporal duration. Specifically, variations in amplitude (Wiener et al., 2012) and latency (Ng et al., 2011) of the Contingent Negative Variation (CNV) component have been observed as a function of the presented stimulus duration, with an activation profile indicating anticipation of the stimulus end (Mento et al., 2013), thus enabling temporal decision making. Additionally, Kononowicz and Rijn (2015) observed an increase in beta oscillatory rhythm detected in SMA, proportional to the duration of the interval produced in a temporal interval reproduction task. The increase in SMA activation as a function of presented stimulus duration was interpreted by Coull and colleagues (2015) as confirmation of the preferential role of this area in the process of accumulation, a key component of temporal perception in the internal clock model (Gibbon et al., 1984). Through an fMRI study, Wencil and colleagues (2010) confirmed Coull and colleagues' hypothesis by identifying a neurofunctional basis for the accumulator in a network that includes SMA. Further confirming the involvement of SMA in accurate time duration perception, a study conducted by Herrmann and colleagues (2014) demonstrated that higher preSMA activation was observed in subjects who exhibited greater resistance to the temporal illusion phenomenon. These subjects were more accurate in an auditory stimulus temporal discrimination task, regardless of the presence or absence of the illusion.

The crucial role of action processing in the subjective time experience opens the possibility of exploring this mechanism within the cinematic context (Gallese and Guerra, 2015). Indeed, action representation finds one of its richest expressions in cinema and editing can be used to control the temporal unfolding of actions depicted in a film (Bordwell, 2013). Previous research has explored the neural mechanisms underlying watching films (Hasson et al., 2008; Heimann et al., 2014) and the impact of various cinematic techniques on viewers' temporal perception (Wied et al., 1992; Cohen et al., 2017). So far, only few studies have examined how editing techniques influence perceived duration of a scene – whether extended or compressed – compared to their actual duration. Editing techniques are typically used by filmmakers in the deliberate attempt to manipulate a scene's perceived duration, given the inherent contrast between actual screen time and narrative time. For example, elliptical editing is used to compress time through omitting parts of an action while maintaining continuity, whereas overlapping editing is used to extend time by repeating action from different angles (Bordwell, 2013).

The first experimental attempt to investigate how editing techniques influence viewers' perception of duration in suspense scenes was conducted by de Wied and colleagues (de Wied et al., 1992), who found that suspense scenes were perceived as lasting longer when preceded by introductory scenes with higher degrees of compression, suggesting that a faster-paced succession of breakpoints enhanced the sense of extended duration.

More recently, Eugeni and colleagues (2020) and Balzarotti and colleagues (2021) investigated how editing density influences viewers' perception of time by modulating the number of breakpoints included in the movie scene. Participants watched video clips with varying editing speeds (fast-paced, slow-paced, and unedited), reporting their duration judgments and subjective time experience. Results revealed a complex pattern within the time experience, with fast-paced editing making time feel as if it passed more quickly but, at the same time, leading to duration overestimation, compared to unedited clips. Authors also found that the viewer's eye movements modulated the effect of editing on duration perception, with shortened fixations and enhanced eye mobility in clips with increased editing density (Balzarotti et al., 2021).

Similar results were reported by Kovarski and colleagues (2022), whose findings revealed that edited scenes – either maintaining spatiotemporal continuity or introducing discontinuity in time, space, and action – were perceived as longer than scenes with no editing. Furthermore the role of arousal, a known predictor of longer perceived duration in previous research (Gil and Droit-Volet, 2012; Droit-Volet et al., 2013), has been investigated, with participants reporting it as higher in the continuous editing condition (Kovarski et al., 2022). It is worth mentioning that the number of breakpoints introduced in each scene and the clip durations differed significantly between Balzarotti and colleagues' and Kovarski and colleagues' studies. In fact, while the fast-paced edited clips used in Balzarotti and colleagues (2021) were in the order of tenth of seconds (11000-13500 ms) and included 10 to 12 breakpoints, Kovarski and colleagues (2022) used much shorter clips (2500-3500ms) including only one editing cut. These differences do not allow for a direct comparison of the results and leave room for discussion on the possible influence of other factors, such as processing load, that may have modulated attentional processes and arousal levels during the viewing experience. A later study by Liapi and colleagues (2024) examined the perceived durations of videos of various actions, manipulated by using three editing techniques: expanded (5 cuts), compressed (3 cuts), and real-time (1 cut). The results showed that expanded (5 cuts) scenes were perceived as significantly longer than both compressed (3 cuts) and real-time (1 cut) scenes, while real-time scenes were also estimated to last longer than compressed ones. To interpret these puzzling results, the authors suggested that the number of breakpoints in the scene is not the only factor influencing participants' perceived duration. Other factors have been speculated to influence duration perception, including the varying actual durations of the scenes, the cognitive resources allocated to non-temporal information (e.g., the scene content), and differences in attentional saliency influenced by motion, colour, and intensity in each scene (Liapi et al., 2024).

1.1 Aim

Based on previous findings that cinematographic editing style affects temporal judgments (Eugeni et al., 2020; Balzarotti et al., 2021), the present study aims to investigate the neural mechanisms underlying this relationship. Specifically, we aimed to study the role of the motor system in time perception during exposure to movie clips depicting actions varying editing densities by modulating the excitability of SMA using transcranial direct current stimulation (tDCS). Non-invasive brain stimulation (NIBS) techniques, such as transcranial magnetic (TMS) and transcranial electric stimulation (tES), have been extensively used to investigate the neural basis of time perception (for a review, see Mioni et al., 2020). Moreover, in numerous studies tDCS was successfully used to modulate the excitability of SMA (e.g., Carlsen et al., 2015; Hupfeld et al., 2017; Nomura and Kirimoto, 2018). Given these premises, tDCS was selected as the optimal technique for our investigation. More precisely, we hypothesized that, enhancing SMA excitability would strengthen the link between motor knowledge and visual motion perception, thereby compensating for subjective time dilation effects and ultimately leading to more accurate duration perception. Conversely, and for the same reasons, we hypothesized that decreased excitability would lead to greater susceptibility to movement-related time dilation biases, resulting in distorted duration perception. Furthermore, we hypothesized that the experience of time passage would vary across stimulation conditions due to differences in duration perception.

2 Materials and Methods

2.1 Participants

Forty-eight undergraduate students aged 21-31 years (M_{age} = 25.1; SD = 2.41; F = 62.5%) volunteered to participate in the study. Students were recruited via email invitations and advertisements on social media platforms. Participants were assigned to one of three experimental conditions (i.e., anodal, cathodal, sham), by stratifying sex (χ^2 = 0.53; ns) and university level (χ^2 = 5.00; ns).

2.2 Transcranial Direct Current Stimulation (tDCS)

A direct current of 1.5mA intensity was generated by a battery-driven stimulator (BrainStim - E.M.S., Bologna) and delivered for 20 minutes through two rubber electrodes, inserted into saline-soaked sponges covered with conductive gel. A 5x5 cm^2 stimulation electrode (either anode or cathode) was placed 1.8 cm anterior to the measured location of Cz (based on the international 10-20 system for EEG electrode placement). A 7x5 cm^2 reference electrode was placed over the right upper arm. The choice of an extra-cephalic montage was to avoid any confounding effect in the brain that could derive from the positioning of the reference electrode. In the control (sham) condition, participants received 1.5 mA of current to give the impression of stimulation, but the current ramped down to 0 mA after a few seconds.

2.3 Video Stimuli

The same experimental stimuli created for Eugeni and colleagues' (2020) and Balzarotti and colleagues' study (2021) were used. Nine video clips representing three action types, performed by a male actor, were shot in a professional studio by an experienced videography crew, using two sets of seven cameras. Video production included nine different shot sizes and angles and the video clips were edited according to three cinematographic editing styles, and specifically: a) master shot, namely, a medium shot with a frontal perspective, with no cuts; b) slow-paced editing, that included four 'match-on-action' cuts, following the rules of continuity; c) fast-paced editing, that included 10-12 cuts and a greater variety of angle/distance changes (e.g., point-of-view shots, plongées, close-ups, cut-in shots) without violating continuity rules. The actor was recorded while performing three action types, that were edited according to each editing style. More precisely, the male actor was instructed 1) to pour water into a glass and drink it ("drinking water"); 2) to cut a loaf of bread using a knife ("cutting bread"); 3) to change the position of a loaf of bread and an empty glass on a table ("moving objects").

2.4 Procedure

Participants' written informed consent was obtained prior the recruitment. After providing demographic information (e.g., age, gender), participants were randomly assigned to one of three experimental conditions: 1) anodal tDCS over SMA, 2) cathodal tDCS over SMA, 3) sham tDCS. After 5 minutes from the beginning of the stimulation, participants were presented with 9 video clips of 10-13 seconds, with different cinematographic editing styles, following Balzarotti and colleagues' procedure (Balzarotti et al., 2021). The order of the clips' presentation was counterbalanced. After each video clip, participants were asked to rate 1) the perceived duration of the clip, by indicating a numerical value between 1 and 30 seconds; 2) the subjective passage of time, on a 9-point scale (1= "Time dragged"; 9 = "Time flew"); 3) the action speed, on a 9-point scale (1= "Very slow"; 9 = "Very fast"). Furthermore, participants were asked to rate their interest, emotional engagement, and boredom on a 7-point scale (1 = "Not at all"; 7 = "Very much") after watching each video clip.

The experimental task was built using PsychoPy v.3.1.0 (Peirce et al., 2019). The study was approved by the Ethics Committee of the Catholic University of the Sacred Heart in Milan, Italy (approval code: 161-24) according to the standards of the Helsinki Declaration (World Medical Association, 2001).

2.5 Analyses

The sample size (n = 48) was calculated to achieve a statistical power of 0.9 for a mixed-design ANOVA (3 x 3), assuming an effect size of 0.25 (Cohen's f) and a significance level (α) set at 0.05. To explore the effects of tDCS, editing style, and action type on time processing (i.e., duration accuracy – calculated as the duration estimate divided by the actual clip duration, time passage, action speed) and emotional involvement (i.e., engagement, interest, boredom), mixed factorial ANOVAs (3 x 3 x 3) with Bonferroni pairwise comparisons was used.

3 Results

3.1 Duration Estimation

The interaction between editing style and tDCS condition yielded a significant effect on duration estimates ($F_{4;180} = 2.74$; $p < .05$; $\eta^2 = .01$). Bonferroni pairwise comparison showed that, in the cathodal condition, the duration of fast-paced edited clips was estimated to be longer compared to the master shot ($p < .05$). Action type main effect was also significant ($F_{2;180} = 9.45$; $p < .001$; $\eta^2 = .02$), with “drinking water” clips generating shorter duration estimates, compared to “cutting bread” ($p < .05$) and “moving objects” ($p < .001$) (Tab. 1). Post-hoc analyses, considering each action type separately, showed that the interaction effect between tDCS and editing style was mainly dragged by “moving objects” clips, in which a clear-cut effect, that confirmed the initial hypothesis, was found ($F_{4;90} = 3.51$; $p < .05$; $\eta^2 = .04$). Participants who received the sham stimulation reporter shorter duration estimates of “moving objects” clips, in the direction of the editing speed increase: the fastest the editing style, the shorter were the duration estimates. Conversely, the opposite trend was found in the cathodal group: The fastest the editing style, the longer were the duration estimates. Furthermore, duration estimates by participants who received the anodal stimulation did not change according to the editing style (Fig. 1).

3.2 Time Passage and Action Speed Judgements

As for the time passage judgments, a significant interaction effect between tDCS and editing style was found ($F_{4;180} = 2.77$; $p < .05$; $\eta^2 = .02$). Post-hoc pairwise comparisons showed that participants who received the anodal stimulation reported that fast-paced edited clips elapsed faster as compared to slow-paced ($p < .05$) and master shot clips ($p < .01$). Therefore, in the anodal group, the faster the editing style of the clips, the higher were the time passage ratings. Moreover, time passage ratings of fast-paced clips by the anodal group were higher than the ratings of the same clips by the cathodal group ($p < .01$). Estimated marginal means showed that participants who received the cathodal stimulation judged the time to elapse slower when the editing style was faster, therefore showing an opposite trend as compared to the anodal group (Fig. 2). Finally, the sham group showed a similar trend to the anodal group, but with lower ratings’ variability between editing styles. However, the aforementioned statistically significant pairwise differences were found without correcting for multiple comparisons.

Consistently with time passage judgments, the interaction between tDCS condition and editing style yielded a significant difference on action speed judgments ($F_{4;180} = 6.58$; $p < .001$; $\eta^2 = .05$). In the anodal group, the actions in fast-paced edited clips were rated faster than those in the master shot clips ($p < .001$), as showed by Bonferroni pairwise comparisons. In contrast, in the cathodal group the faster the editing’s pace, the slower were the action speed ratings (Fig. 3), therefore showing an opposite trend. Participants who received the sham stimulation showed slightly increasing ratings along with the editing’s pace, however with lower variability than the anodal group.

3.3 Emotional Involvement

The editing style, but not tDCS nor action type, affected the emotional involvement of participants. A significant main effect of editing style emerged on engagement ratings ($F_{2;180} = 4.55$; $p < .05$; $\eta^2 = .01$). Bonferroni pairwise comparisons showed that fast-paced edited clips were rated as more engaging than the master shot ($p < .05$). Similarly, the analysis yielded a significant main effect of editing style on interest ($F_{2;180} = 8.16$; $p < .001$; $\eta^2 = .01$), with fast-paced edited clips rated as more interesting than the master shot ($p < .001$), as shown by the pairwise comparisons. Finally, boredom was not affected by any of the considered independent variables.

4 Discussion

The modulation of SMA excitability affected the objective (i.e., duration estimates) and subjective (i.e., time passage and action speed judgments) measures of time perception, by interacting with the editing style of the clips.

Consistently with our initial hypothesis and with the neuroscientific evidence showing SMA involvement in accurate temporal processing (e.g., Coull et al., 2015), an increased excitability of SMA induced duration perceptions which were not susceptible to editing style influences. Participants who received anodal stimulation over SMA did not adjust their duration estimates according to the editing style, but instead reported consistent estimates, regardless of the editing density. This result is in line with the fMRI findings by Herrmann and colleagues (2014), showing that SMA activation was a predictor of individual differences in temporal-change sensitivity, with reductions in susceptibility to illusory distortions. We suggest that enhanced SMA excitability facilitated the development of a temporal visuomotor representation shaped by motor knowledge of human actions which assured a more precise matching between the internal models of action and the visual kinematics of the observed motion. This, as a result, improved the temporal mechanism of visual motion, compensating for temporal sensory limitations caused by subjective time dilation effects. In contrast, a decreased neuronal excitability of SMA through cathodal stimulation yielded duration estimates directly influenced by the movement density, namely, the duration of fast-paced edited clips was estimated to be the longest, while the master shot clips were estimated to be the shortest. That is consistent with the subjective time dilation induced by visual stimulus velocity (Kanai et al., 2006; Tomassini et al., 2011). We argue that such bias could not be effectively modulated by exploiting sensorimotor representations due to the inhibition of SMA involvement.

The duration estimates were also influenced by the type of action represented in the clips. More precisely, the three actions differed in terms of intentionality and goal-orientation and, therefore, in terms of predictability. The clearest the intentionality of the action, as in "drinking water" clips, the easiest is the anticipation of the action's ending. On the contrary, the endings of actions with an undefined global intention (i.e., the "moving objects" clips) are the most difficult to anticipate. Our results, consistently with Eugeni and colleagues' findings (2020), showed that the clarity of intentionality influenced the duration estimates: More predictable actions were estimated to be shorter than less predictable ones. Indeed, previous evidence has shown that individuals tend to perceive the onset of predictable movements as delayed while anticipating their consequences, leading to an underestimation of their duration (Haggard et al., 2002). The interaction effect between neuromodulation and editing style was found to be stronger in the "moving objects" clips. We argue that the non-predictability of this action assured a duration measure which was free of potential anticipatory biases.

As regards the subjective experience of time passage, the modulation of SMA excitability had an opposite effect on time passage and action speed judgments of clips with different editing style, as a function of neuromodulation polarity (i.e., anodal vs cathodal). More precisely, the anodal stimulation amplified the effect of editing speed on temporal subjective judgments, in the direction of faster time passage and faster action perceptions along with faster editing pace. This effect is consistent with the findings of Balzarotti and colleagues (2021) showing that an increased number of breakpoints in a scene influenced time judgments, accelerating the perceived flow of time. Consistently, previous results from Wearden (2005) showed that participants perceived time as passing more quickly while watching an action film with a fast editing style compared to a relaxation film. The direction of such effect was reversed by the cathodal stimulation: The time passage and action flow were perceived to elapse slower in faster-paced edited clips. While earlier studies (Droit-Volet and Wearden, 2016; Droit-Volet et al., 2017) suggested that judgments of time passage are unrelated to duration perception, more recent evidence (Martinelli and Droit-Volet, 2022) indicates that the perceived speed of time increases as stimulus duration decreases, aligning with our results.

This study is the first to explore the neural basis of time perception in relation to movie clips with different editing styles. Our findings highlighted the role of SMA in modulating time perception during film viewing, showing that the increased involvement of the sensorimotor system produces more accurate duration estimates, while its inhibition enhances susceptibility to editing-induced distortions. Additionally, the predictability of actions influenced time perception, with clearer intentionality leading to shorter perceived durations.

This investigation offers an important contribution by bridging neuroscience and film studies, shedding light on how embodied mechanisms underpin the perception of cinematic time. In particular, these conclusions open up a broader discussion about the specificity of the film viewing experience compared to the ordinary one. In fact, it can be assumed that the cinematic experience is profoundly shaped by the multiplicity of stimuli of moving objects and subjects: the actors engaged in the actions, the camera, the editing itself perceived as a form of shifting the point of view. The need to coordinate these different flows into a coherent pattern produces the temporal nature of the audiovisual viewing experience, also through a specific and peculiar involvement of the SMA.

Future studies should investigate a wider range of actions and editing techniques to further disentangle the interplay between sensorimotor representations and temporal processing. Expanding this line of research could provide a more comprehensive understanding of the factors shaping time perception in dynamic visual contexts.

5 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 Author Contributions

Conceptualization: ER, SB, AC. Data curation: AC. Formal analysis: AC. Funding Acquisition: ER, AD. Investigation: AC. Methodology: AC, SB. Project administration: ER, AD. Resources: ER, AD. Supervision: ER, AA, AD, SB. Writing – original draft: AC. Writing – review & editing: AC, AA, ER, SB.

7 Funding

PRIN 2017-2019 (National Interest Research Projects - ITALY) Perception, Performativity and Cognitive Sciences (grant number: 2015TM24JS–SH4).

8 Acknowledgments

We thank Sabrina Rago, Giacomo Placucci and Federica Cavaletti for their role as research assistant in the experiment.

9 Data Availability Statement

The datasets generated for this study will be made available upon reasonable request.

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Tab. 1 – Duration accuracy estimates (Editing style x tDCS Condition x Action type)

Action Type	tDCS	Editing Style	Mean	SD
Drinking water	SHAM	Master shot	0.671	0.450
		Slow-paced	0.653	0.273
		Fast-paced	0.699	0.285
	ANODAL	Master shot	0.722	0.298
		Slow-paced	0.750	0.243
		Fast-paced	0.796	0.359
	CATHODAL	Master shot	0.755	0.380
		Slow-paced	0.870	0.298
		Fast-paced	0.926	0.304
Cutting bread	SHAM	Master shot	0.699	0.204
		Slow-paced	0.813	0.440
		Fast-paced	0.847	0.537
	ANODAL	Master shot	0.790	0.300
		Slow-paced	0.841	0.287
		Fast-paced	0.790	0.283
	CATHODAL	Master shot	0.841	0.400
		Slow-paced	0.864	0.304

		Fast-paced	1.057	0.386
Moving objects	SHAM	Master shot	0.969	0.517
		Slow-paced	0.837	0.461
		Fast-paced	0.742	0.260
	ANODAL	Master shot	0.853	0.265
		Slow-paced	0.853	0.248
		Fast-paced	0.810	0.327
	CATHODAL	Master shot	0.885	0.340
		Slow-paced	0.906	0.347
		Fast-paced	1.065	0.429

Fig. 1 – Duration accuracy estimates of the "moving object" clips (Editing style x tDCS Condition)

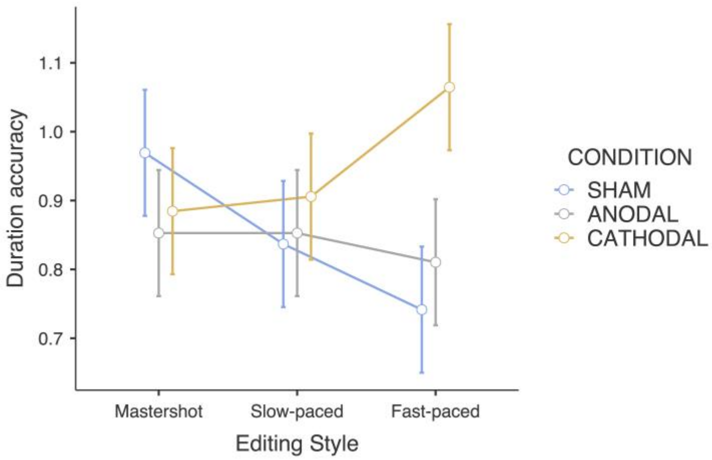

Fig. 2 – Time passage judgments estimated marginal means (Editing style x tDCS Condition)

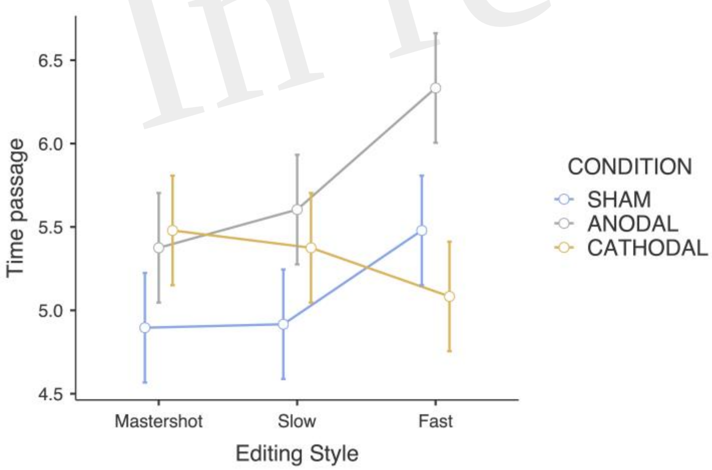

Fig. 3 – Action speed judgments estimated marginal means (Editing style x tDCS Condition)

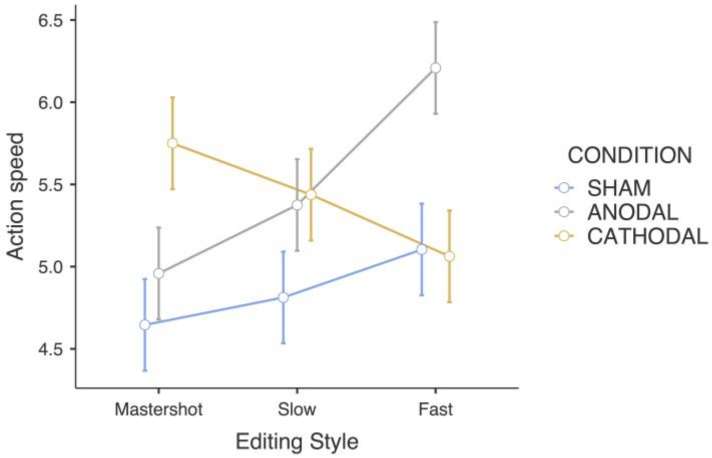
Action speed
6.5
6.0
5.5
5.0
4.5
Mastershot
Slow
Fast
Editing Style
CONDITION
SHAM
ANODAL
CATHODAL

Figure 1.JPEG

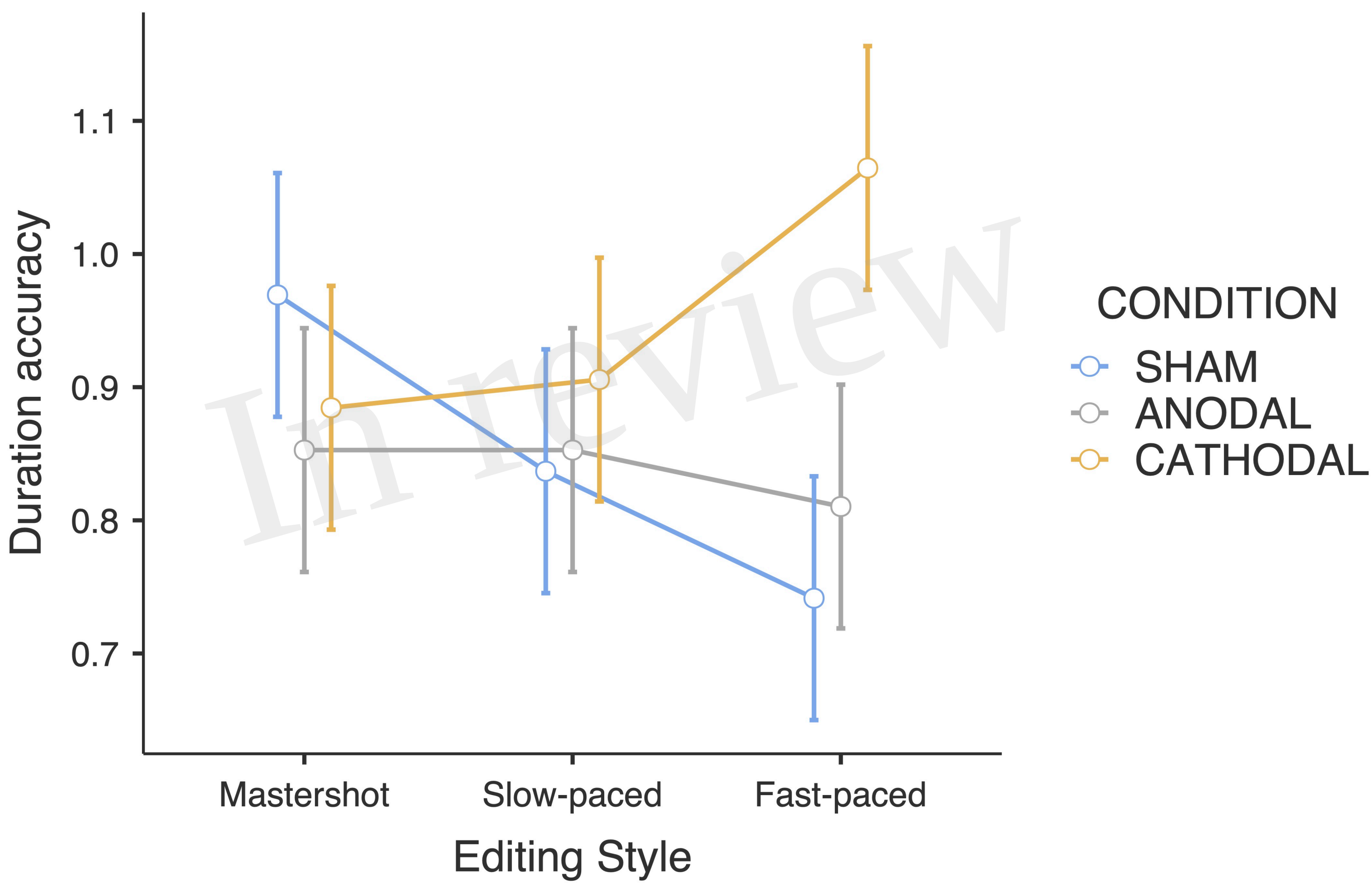

Figure 2.JPEG

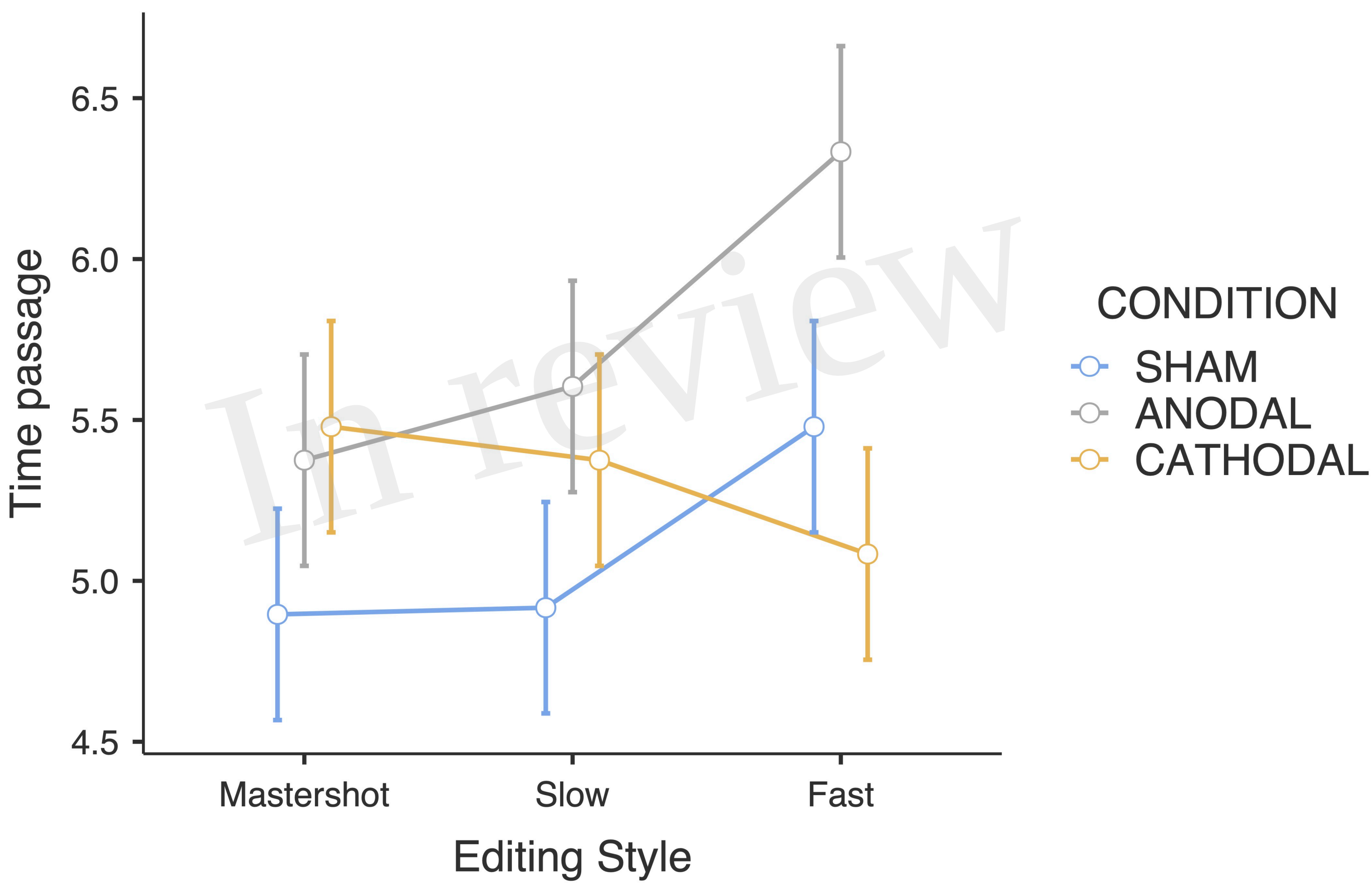

Figure 3.JPEG