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General tau theory as a model to evaluate audiovisual interplay in interceptive actions

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ABSTRACT

When interacting with the environment, sensory information is essential to guide movements. Picking up the appropriate sensory information (both visual and auditory) about the progression of an event is required to reach the right place at the right time. In this study, we aimed to see if general tau theory could explain the audiovisual guidance of movement in interceptive action (an interception task). The specific contributions of auditory and visual sensory information were tested by timing synchronous and asynchronous audiovisual interplays in successful interceptive trials. The performance was computed by using the tau-coupling model for information-movement guidance. Our findings revealed that while the auditory contribution to movement guidance did change across conditions, the visual contribution remained constant. In addition, when comparing the auditory and visual contributions, the results revealed a significant decrease in the auditory compared to the visual contribution in just one of the asynchronous conditions where the visual target was presented after the sound. This may be because more attention was drawn to the visual information, resulting in a decrease in the auditory guidance of movement. To summarize, our findings reveal how tau-coupling can be used to disentangle the relative contributions of the visual and auditory sensory modalities in movement planning.

1. Introduction

Being able to pick up and tune into relevant sensory information in the surrounding environment that specifies the dynamics of an unfolding event, is critical to the prospective control of movement. Effective control of movement has been shown to involve different types of sensory information (Ernst & Banks, 2002; Ernst & Bülthoff, 2004; Hillis et al., 2002; Vroomen & Gelder, 2000), through the modulation of their relative contribution (Brendel et al., 2012; Hecht et al., 2002; Hecht & Reiner, 2008; Hodges, 2005; Kim et al., 2011; McDonald et al., 2000; Pick et al., 1969; Posner et al., 1976; Shams et al., 2000; Song et al., 2017; Sugano et al., 2015; Tremblay & Nguyen, 2010) but also by selecting preferentially one type of sensory information at the expense of others as a function of the task requirements (Colavita, 1974; Colavita & Weisberg, 1979; Egeth & Sager, 1977; Hecht & Reiner, 2008; Lee & Aronson, 1974). Even considering the "modality appropriateness" hypothesis that includes the influence given by the task specificity in requiring the benefit of perceptual modality (Welch & Warren, 1980) it is important to underline that in general visual information is used more efficiently during action planning and action performance than auditory information (Glazebrook et al., 2016). For example, when considering the role of audiovisual information, Colavita and colleagues studied the interplay between visual and auditory information when performing reaction time tasks (Colavita, 1974; Colavita & Weisberg, 1979). In these studies, participants were presented with just one sensory cue at a time, either auditory (tone) or visual (light) and were then asked to react as fast and precisely as possible as soon as the cue appeared (i.e., press the "tone key" if it was an auditory cue, or press the "light key" if it was visual). Unbeknownst to the subjects, catch trials were included, where both auditory and visual cues were presented at the same time. Although the results showed shorter latencies for visual compared to auditory stimuli (Colavita, 1974), the open question remains as to how the relationship between auditory and visual information would play out if the task was not just a reaction time one but was an interceptive task instead.

Putting the sensory-driven reaction time studies aside, General tau theory provides a parsimonious description of sensory (either visual and/or auditory) guidance of movements in goal-directed actions.

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General tau theory describes how goal-directed movements are prospectively controlled using sensory information (Lee, 1998), but also how reflexive movements can also be guided using intrinsically generated sensory information (Bahadori et al., 2021).

In short, this theory explains how different patterns of information picked up by the brain (externally and internally) can prospectively guide the control of various forms of biological movement (Lee, 1976; Lee, 1998; Lee et al., 1982; Lee & Young, 1985). Since tau (τ) specifies the time to closure of an action gap ($\tau_x = x/\dot{x}$; x denotes the action gap and $\dot{x}$ is its rate of change), the main assumption of the theory is that each tau represents the changing time gap between a current state and a goal state, while different taus, corresponding to different action gaps, are closely coupled together (Lee, 1998) to achieve a task outcome such as arriving at the same place at the same time as is the case for interception.

Information specifying the rate of closure of action gaps can be picked up through the senses (extrinsic tau) (Lee, 1998) or generated intrinsically by the CNS (tau guide). For example, when catching a ball, the ball's time to arrival is specified by the tau of the changing ball-hand gap picked up through the eyes (Lee et al., 2001). Conversely, when intercepting an invisible moving sound source, the time to arrival of the sound source is picked through the changing patterns of auditory information specifying the rate of closure of the gap (between the listener and the sound) at its current closure rate (tau) (Komeilipoor, Rodger, Cesari, & Craig, 2015; Komeilipoor, Rodger, Craig, & Cesari, 2015). Ultimately, whatever information is available, (visual or auditory), the successful interception of a target, happens if the tau of the hand-target action gap (τ_y) is linearly coupled to the tau of the hand-arrival action gap (τ_x) ($\tau_y = k\,\tau_x$, where k is a constant coefficient to describe how the gaps close together) (Lee, 1998).

In this study, we aimed to investigate the role of auditory and visual information when performing goal-directed movements. To fulfill this aim, we tested the tau theory as a model to disentangle the relative contribution of each source of sensory information when performing an interceptive action. Tau theory was used as a model for the following reasons: 1) it is a simple and elegant method for modeling information-movement coupling (Lee, 1998), and 2) it can quantify the relative contribution of visual and auditory sensory information in goal-directed movement (Komeilipoor, Rodger, Cesari, & Craig, 2015; Lee et al., 2001; Smith et al., 2014), allowing for a better understanding of the interplay between audio and visual information when performing goal-directed movements. The materials and methods are explained in Section 2. Section 3 outlines the analysis and presents the results of the information-movement coupling with respect to the visual and auditory components. The discussion is presented in Section 4.

2. Materials and methods

2.1. Participants

To determine the number of subjects to recruit, the sample size was calculated using G-Power (Faul et al., 2007) for F tests, repeated measures within interactions. Considering a medium effect size of 0.25 (Cohen, 1988), an error probability of 0.05, a power (1-β error probability) of 0.8, 5 measurements (details in Table 1), a correlation of 0.5 among repeated measures, and non-sphericity correction ε of 1, the resulting sample size was 21. Accordingly, twenty-one healthy right-handed participants (age: mean ± SD = 23.9 ± 4 years) (fourteen females) participated in the study. All participants reported that they had no problem with hearing or vision and had no history of any neurological disorders or pathologies.

2.2. Task

The individuals were placed in front of a monitor screen (34.5 × 19.5 cm) positioned at 70 cm from their eyes. They were seated in front of the display in such a way that their sagittal plane passed through the monitor's right side (Fig. 1, top). At the start of each trial, one circle (representing the initial position) was displayed on the bottom right side of the screen that could be manipulated directly by the participant's hand movement (Fig. 1, bottom left). Another circle appeared on the top left hand corner of the screen (target, Fig. 1, bottom left) and moved horizontally along the top towards the right hand corner of the screen (Fig. 1, bottom right). The hand circle was the object that the participant could move vertically (bottom to top) so the participant could intercept the moving target (target).

Table 1
Experimental Conditions. Two unimodal conditions (1 and 2), including just visual or auditory stimuli, and three bimodal conditions (3, 4, and 5). The two unimodal conditions were placed at the start of the experiment (visual first, then auditory), and the other three bimodal conditions were performed randomly after that.

	Condition		Description
1	VO	Visual only	Intercepting a visual target that moved left to right along the screen.
2	AO	Auditory only	Intercepting an auditory target that moved left to right along the screen.
3	VAS	Visual-auditory synchronous	Intercepting a visual-auditory target. The position of the visual target and the position of the sound source were co-located, so they were always perceived to be in the same place.
4	VAd	Visual target first and auditory target delayed	Intercepting a visual-auditory target. The position of the source of the sound was delayed compared to the position of the visual target. This meant that the sound started to play at a fixed time after the visual target started to move. It should be noted that the pattern of displacement for both the visual and sound sources were calculated in the same way.
5	VdA	Visual target delayed compared to the auditory target	Intercepting an auditory-visual target. The movement of the visual target started after the movement of the sound source. This meant that the visual target started to move a fixed time after the sound source started to move (VdA). As for the VAd condition, the patterns of displacement for both the visual and sound sources were calculated in the same way.

There were two types of moving targets: 1) a visible, visual-only target with no sound, and 2) an invisible, auditory-only target with sound. The target moved horizontally from the top left corner to the top right corner of the screen (27.6 cm) under both scenarios. Subjects were requested to use a trackpad to direct the movement of their hand from the bottom right corner to the top right corner (around 17.6 cm distance; Fig. 1, bottom). When the participant clicked the mouse, the target and the hand both appeared on the screen against a white background. The participants were instructed to intercept the target with a single direct movement by their hand.

2.2.1. Apparatus

We picked a high-performance gaming trackpad (A4tech Bloody) to record the hand movements that controlled the hand object on the screen. The latency was calculated at 1 ms, the sensitivity ranged from 800 to 8200 dpi, and movements could be tracked with accelerations up to 30 g. We adjusted the trackpad's sensitivity to obtain a one-to-one mapping between the displacement of the hand object on the screen and the real hand displacement using the trackpad. The monitor refresh rate was set at 60 Hz. We developed a Matlab toolbox (MathWorks Inc., R2014) to run the experiment and record the data. The sampling frequency for data collection was set at 600 Hz. Subjects wore conventional earphones to receive the auditory stimuli (Beyer Dynamic, DT-770). As a

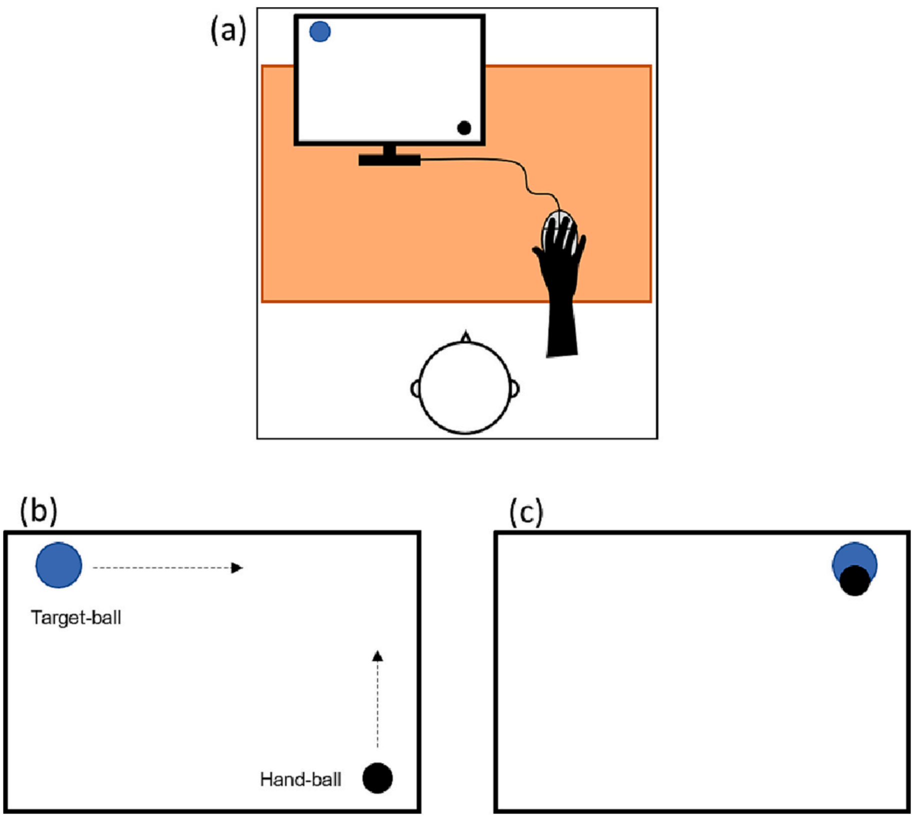

Fig. 1. A schematic diagram illustrating the interception task presented on the screen of a monitor. a) the participant seated in front of the screen, b) The target (visual target-ball on the figure) was placed on the top left hand side of the monitor screen at the start of each trial, and the hand (hand-ball on the figure) was placed on the bottom right hand side of the monitor screen. c) The participant had to control the timing of the movement of the hand using the trackpad, so it intercepted the target on the top right side of the monitor screen. The target moved around 27.6 cm horizontally, while the cursor moved roughly 17.6 cm vertically.

consequence, visual feedback was provided within a time window of <19 ms (display delay plus cursor and recording delay) (Smith & Bowen, 1980). Considering that the 19 ms delay could be sufficient to elicit a small yet non-negligible alteration in visuo-motor coordination processes (Smith, 1972; Smith & Bowen, 1980).

2.3. Stimuli

On the screen, the position of the auditory and visual stimuli (the two targets) was computed using Eq. (1).

$$x_i(t) = 0.5a_i t^2 + v_{0,i} t \tag{1}$$

where *x(t)* defines the target's horizontal position, *t* denotes time, *a* denotes acceleration, v_0 denotes the target's initial velocity, and *i* denotes the type of target. For the purposes of programming the experiment $i = 1$ corresponded to a visible target, and $i = 2$ corresponded to an invisible target.

A burst of 700 Hz pure tones with a duration of 45 ms served as the sound stimulus (Komeilipoor, Rodger, Cesari, & Craig, 2015). A burst of tone, as opposed to a continuous tone, is said to stimulate better the auditory system (Frith & Friston, 1996).

To create a stereo stimulus, the Interaural Time Difference (ITD) was determined and applied to the simulated sound. The approximate radius of a typical human head was used in the ITD calculation of 8.75 cm (Algazi et al., 2001). Using an inverse square law, the intensity of sound delivered to each ear was modulated by the distance at each moment in time (Fig. 2) (Coleman, 1963). Finally, to prevent the participants from experiencing a startle reflex, the generated sound was delivered through isolated headphones at a maximum intensity of 70 dB sound pressure level (SPL) (Camponogara et al., 2015; Finisguerra et al., 2015).

2.4. Preprocessing

A second-order Butterworth low-pass filter with a cut-off frequency of 15 Hz was used to filter the raw data (Camponogara et al., 2015). The time of interception was set to zero, according to Lee et al. (2001). If the distance between the visual or the auditory stimuli (invisible on the monitor screen) and the hand was smaller than a pre-defined threshold

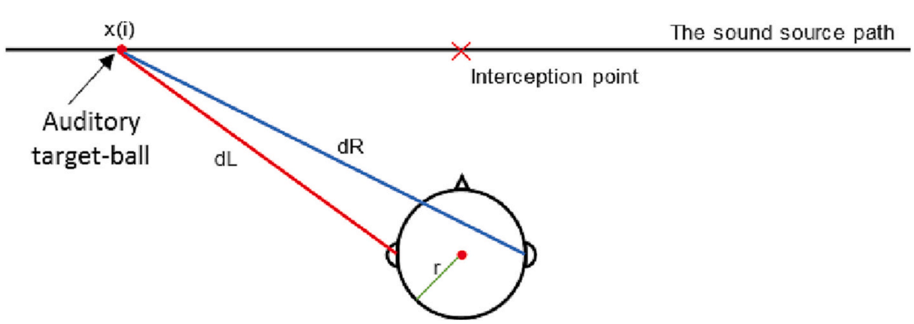

Fig. 2. A schematic illustration of the spatial location of the simulated auditory stimulus. x(t) is the intensity of the sound at t, which is modified by dR and dL for the right and left ear.

(i.e., the sum of the target and cursor radii), the interception moment was deemed to have occurred. The sum of the target and hand radii was used to set this criterion. The goal was defined as the point of interception. The movement initiation was detected at a velocity exceeding 10 % of the peak movement velocity (Lee et al., 2001). Movements were analyzed between the start of the movement and the point of interception (or the time when the target was missed).

2.5. Calculating tau of action gaps

To determine the visual guidance of hand movement, the tau of the hand-goal action gap (τ_{HG}) and hand-target action gap (τ_{HT}) were calculated using Eqs. (2) and (3), respectively.

$$\tau_{HG} = x_{HG}/\dot{x}_{HG} \tag{2}$$

$$\tau_{HT} = x_{HT}/\dot{x}_{HT} \tag{3}$$

where the dot is the first derivative operator, x_{HG} is the distance between the hand and the goal, and x_{HT} is the distance between the hand and the target (Lee et al., 2001). To identify the auditory guidance of movement, the tau of *ITD*, which was the rate of change of the *ITD* in time, was computed using Eq. (4) (Komeilipoor, Rodger, Cesari, & Craig, 2015; Lee, 1998).

$$\tau_{ITD} = ITD/\dot{ITD} \tag{4}$$

2.6. Experimental conditions

Under various visual and auditory stimuli, participants were asked to intercept the target (Fig. 3). To investigate the effects of sensory modalities on movement guidance, we defined two unimodal conditions (just visual or auditory stimuli) and three bimodal (both visual and auditory stimuli) conditions (Table 1). It is worth noting that the unimodal conditions were always placed at the beginning of the experiment.

Each experimental condition consisted of 20 trials. Subjects performed a training session consisting of the same number of trials before starting the experimental conditions. The visual target and sound source were synchronized in the VAS condition, with the acceleration set at 0.15 m/s^2 and the initial velocity set at 0 m/s. In the VAd condition, the sound source (the invisible auditory target) began 300 ms after the visual target. We chose this time interval since it has been shown that if the auditory stimulus follows the visual stimulus within 150 ms, both stimuli are perceived as being synchronous (Koppen & Spence, 2007). Instead, in the VdA condition, the visual target began 300 ms after the sound source. In this condition, the delay is also in a time span larger than the temporal synchronization assumption when a visual stimulus precedes an auditory stimulus (35 ms) (Koppen & Spence, 2007).

In the experimental procedure design, participants first performed the unimodal condition blocks (i.e., VO and AO) in a randomized order among participants. Afterward, they performed the bimodal condition blocks (i.e., VAS, VAd, VdA) also performed in a randomized order among participants. A two-minute rest between two consecutive condition blocks was considered. Moreover, a 10-s rest was considered between two consecutive trials. The number of trials for each condition was 20, i.e., a total of 100 trials in the whole experiment for each participant. The experiment lasted for around 5 min for each condition block and around 33 min in total.

2.7. Tau coupling between action gaps

For both the visual and auditory target action gaps (Fig. 4), the extent of tau coupling between the hand-goal (HG) and hand-target (HT) was calculated using the approach proposed by Smith et al. (2014). The aim was to calculate the percentage of the movement where the tau of the Hand-goal gap τ_{HG} and the tau of the hand target gap τ_{HT} are linearly coupled with r^2 values >0.97.

The following method was used. First, as mentioned in Section 2.5, the taus of the two motion gaps (τ_{HG} and τ_{HT}) were calculated (Fig. 4) with τ_{HG} being plotted against τ_{HT}. Each movement trial had N data points, with the first data point corresponding to the start of the movement and the last data point corresponding to the moment of interception. A linear regression was then fitted to the data points starting from the movement's endpoint (N^{th} point) to the $(N\text{-}L)^{th}$ point. We increased the *L* value (starting from 1) until the linear regression's r^2 dropped below 0.97. The movement percentage (*MP*) is computed using $MP = (L / N) \times 100\,\%$. The MP calculated from visual information (i.e., τ_{HT}-τ_{HG}) was called MPVisual, and the MP calculated from auditory information (i.e., τ_{ITD}-τ_{HG}) was called MPSound. The mean values of MPVisual and MPSound in a session were deemed the representative values of sessions for further analysis after computing the MPVisual and MPSound for successful trials for each participant in each session.

2.8. Statistical analysis

A Repeated measures ANOVA (rmANOVA) was used for MPV and MPS separately, taking into account all conditions. The effect size was determined using η_p^2 and Cohen's d for the main effect of condition and post hoc analysis, respectively (Fritz et al., 2012). When necessary, a Bonferroni correction was applied, and the level of significance was set at $p \leq 0.05$.

3. Results

The analysis includes the successful trial interceptions (VO: 71.4 %, AO: 39.5 %, VAS: 74.5 %, VAd: 77.9 %, and VdA: 74.3 %). The success

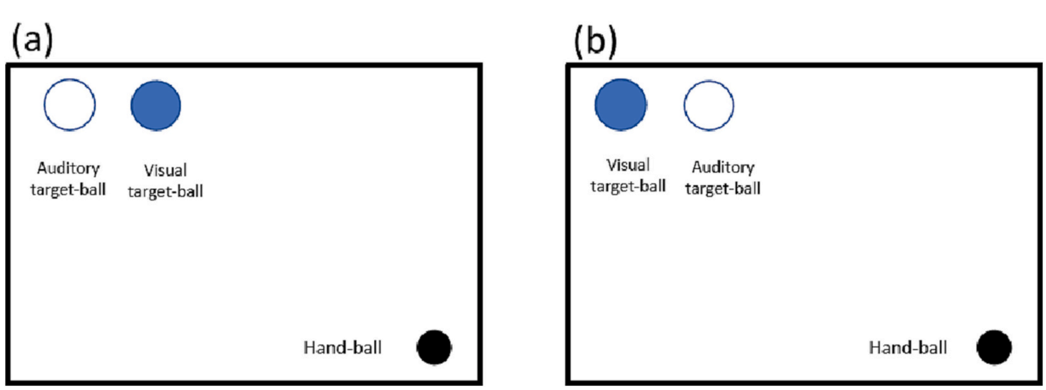

Fig. 3. A diagram representing the relative placement of the targets in the Visual-Auditory delayed conditions. a) VAd condition (visual target ahead of the auditory target). b) VdA condition (auditory target ahead of the visual target).

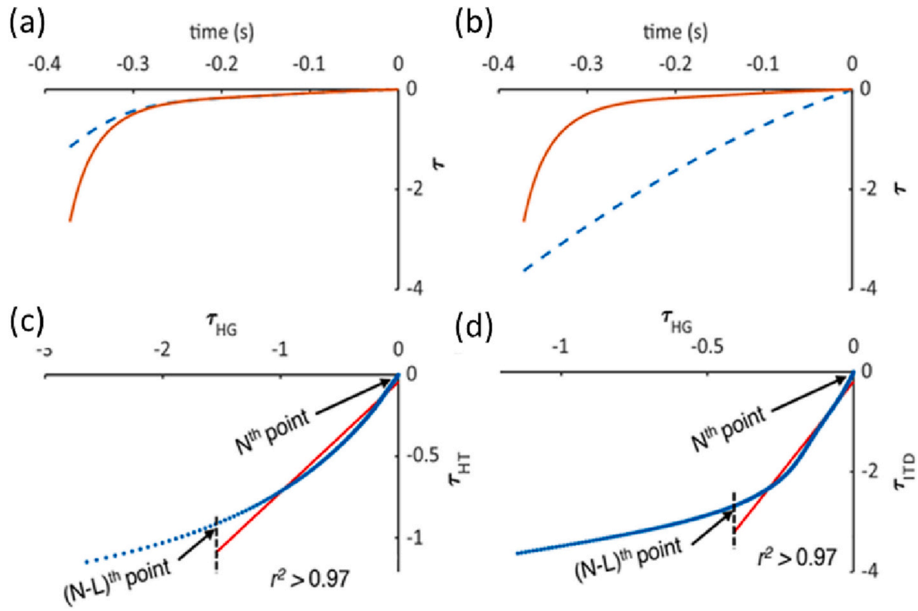

Fig. 4. The tau of hand-goal (red line) and hand-target (dashed blue line) for visual (a) and auditory (b) action gaps. In the bottom graphs, the linear regression (red lines) were plotted for hand-goal versus hand-target (blue dotted lines) for visual (c) and auditory (d) targets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rate of AO was not very high similar to Komeilipoor, Rodger, Cesari, and Craig (2015). A significant main effect for Condition was found for success rate ($F_{(4,80)} = 36.25$, $p < 0.001$, $\eta_p^2 = 0.644$) with lower values being found for the AO condition compared to all the other conditions ($p < 0.001$). In subsequent analysis, we used the success rates as covariates in the statistical analysis, although this had no statistical impact on the results. In this case, no covariate was taken into account when reporting the results.

MPVisual data revealed no significant effect for Condition ($p = 0.341$) whereas MPSound revealed a significant main effect for condition ($F_{(3,60)} = 17.56$, $p < 0.001$, $\eta_p^2 = 0.468$). The post hoc analysis for MPSound, showed VdA (57.25 ± 2.05 %) to be significantly lower than AO (69.63 ± 3.37 %; p = 0.007, Cohen's d = 1.26) (Fig. 5). Furthermore, when comparing the bimodal conditions, the VAS condition (74.48 ± 2.06 %) had higher MPSound values than the other asynchronous conditions (VAd: 64.25 ± 1.42 %, VdA: 57.25 ± 2.05 %; for all comparisons, $p < 0.001$, $d > 2.32$) (Fig. 5). Besides, VAd had higher MPSound values compared to the VdA condition ($p = 0.001$, $d = 2.63$). No other comparisons were found to be significant (for all comparisons, $p > 0.124$) (Fig. 5).

4. Discussion

We investigated the interplay between visual and auditory information when intercepting moving auditory and visual targets. By using tau theory as a model and calculating MPVisual and MPSound values we were able to compare the relative contributions of visual and auditory sensory information when making a goal-directed movement. Although no significant differences were found between MPVisual in either unimodal or bimodal synchronous and asynchronous conditions, this was not the case for MPSound. When both auditory and visual information sources are present in a forced-choice reaction time task, it has previously been shown that people had shorter latencies with visual information (Colavita, 1974; Colavita & Weisberg, 1979). Of note, given that MPVisual remained stable across audiovisual and unimodal conditions, it may also be stated that visual information is more salient than auditory information when it comes to prospectively guiding movement.

The MPSound data instead showed that there were substantial variances between conditions. When comparing the unimodal and the bimodal conditions, the VdA bimodal condition demonstrated a significant reduction compared to the unimodal AO.

Previous studies have demonstrated that when attention shifts from audition to vision, activity in the visual cortex increases while activity in

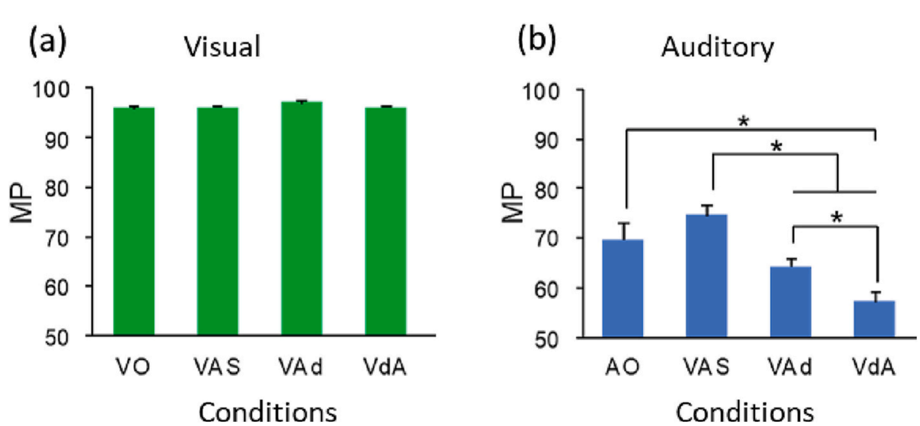

Fig. 5. The MPVisual (a) and MPSound (b) are shown for the different conditions. Asterisks show statistically significant differences (* ρ ≤ 0.05).

the auditory cortex decreases (Shomstein, 2004). In this regard, we hypothesize that because the salient visual information occurs after the auditory information in the VdA condition, salience of the auditory information is less, resulting in a reduction in the auditory guidance of movement. It is worth mentioning that presenting visual information before auditory information increases the chance of both stimuli being perceived as being simultaneous (Jaśkowski et al., 1990; Koppen & Spence, 2007; Slutsky & Recanzone, 2001; Van Eijk et al., 2008). If this is the case, we would hypothesize the MPSound in the VAd condition to be higher than in the VdA condition. Of note, one might conclude that presenting visual information after auditory information may cause more attention to be drawn to the visual information, resulting in a decrease in the auditory guidance of movement in the VdA condition.

Additionally, it has been found that when audition came first, the shift in the point of subjective simultaneity was substantially lower (Diederich & Colonius, 2015; Van der Burg et al., 2013). The auditory cortex may also adapt its timing to the visual-spatial anchor, according to consistent changes in the phase of auditory neural responses but not visual ones (Kösem & Van Wassenhove, 2012).

To our knowledge, this is the first study investigating the audiovisual interplay while performing interceptive actions. When intercepting a target in a pre-specified zone, we applied tau theory as a model to quantify the relative contribution of each source of sensory information. In both unimodal and bimodal conditions, visual information was preferred over auditory information in goal-directed movement. Importantly, we showed that tau theory could be utilized to understand the contribution of different types of sensory information. Tau theory, as a model capable of investigating the role of audiovisual information in movement guidance, could be utilized in the future to better understand the role of different types of sensory information in goal-directed movements.

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Ethical approval and consent to participate

All procedures of the experiment followed the institutional ethical standards, in line with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. This study was approved by the local ethics committee of the University of Isfahan and all the participants gave written informed consent.

Consent to publish

All participants provided consent to publish data associated with the study.

CRediT authorship contribution statement

MEA and MB designed and planned the experiment. MB prepared the software, collected, exported, and prepared the data. MEA and MB analyzed the data. MB and MEA drafted the manuscript, created the figures and tables. PC, CC, and JR revised the manuscript. All authors read and approved the final version of the manuscript.

Declaration of competing interest

All authors declare no conflict of interest.

Data availability

Data collected for this study are available by request through the corresponding author.

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