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Toward the manipulation of time and space in extended reality: a preliminary study on multimodal Tau and Kappa illusions in the visual-tactile domain

Yuri De Pra, Vincenzo Catrambone, Virginie van Wassenhove, Gaetano Valenza and Matteo Bianchi

Abstract— **In the last few years, Extended reality (XR) has enabled novel forms of sensory experiences and social interplay, which can be hardly experienced in real life. However, the full potential of XR has not been exploited yet, since vision remains the main interaction modality, and the time- and space-modulation of the sense of self - which could open interesting perspectives in several scenarios - is still largely unexplored. To pave the path to a multi-modal manipulation of the sense of time and space in immersive XR, in this work we discuss the preliminary outcomes of the first investigation in the visual-tactile domain of two well known perceptual illusions affecting spatial and temporal perception, i.e. Tau and Kappa effects, respectively. We compared the effects originated from unimodal stimulation (i.e., only visual or tactile) with the same effects induced by convergent bimodal stimulation (i.e., visual and tactile), delivered to the forearm. Results show that both Tau and Kappa effects are affected by the multi-modality of the stimulation, and that the perceptual bias differently affects time- or space- perception based on the modality used for stimulus delivery. Our results, although preliminary, seem to suggest that multimodal perceptual illusions could be a viable solution for time- and space- modulation of the sense of self in immersive XR and advanced social human-robot interaction.**

I. INTRODUCTION

In the last few years, the mass scale diffusion of the eXtended Reality (XR) systems, which refer to all real-and-virtual combined environments for advanced human-machine interaction, including virtual (VR), augmented (AR), and mixed reality (MR), has opened new perspectives in multiple fields such as medicine, engineering, and arts [1]. The effectiveness of VR was demonstrated, for example, in several psychological treatments, where usage the of *safe* and controlled virtual worlds enabled patients to experience new realities without feeling threatened [2]. The boost for the success of XR systems mainly came from the sense of spatial presence [3] elicited through advanced devices for realistic visual rendering, such as head-mounted displays (HMD) [4]. However, an effective multi-modal interaction that encompass both the visual and tactile channel is still far to be accomplished, despite the promising developments of wearable haptic systems [5], such as haptic gloves and suites [6]. This multimodality could help in improving the sense of immersion and the customization of the experience, shifting the peripersonal space to the virtual representation of self in VR [7], improving social human-robot interaction.

Y. De Pra, V. Catrambone, G. Valenza and M.Bianchi are with the “E. Piaggio” Research Center, University of Pisa, Italy.

V. Catrambone, G. Valenza and M.Bianchi are with the Department of Information Engineering (DII), University of Pisa, Italy

V. van Wassenhove is with CEA DRF/Joliot, NeuroSpin; INSERM, Cognitive Neuroimaging Unit; CNRS; Université Paris-Saclay, Gif-Sur-Yvette, France

Under this regard, an aspect related to multimodality for XR that has received little or no attention is its usage for the modulation of time and space perception, relying on perceptual multi-modal biases induced in the users. These multi-modal biases were already successfully used in VR, e.g. to improve the perceived resolution of encountered-type haptic devices [8]. However, the investigation of visuo-tactile illusion for manipulating the sense of self in time and space has not been performed yet. In this work, we present a preliminary study on the effects that visuo-tactile stimulation can produce with respect to well-know illusions on space and time perception, namely the Tau Effect and the Kappa Effect, respectively. In the Tau effect, the space distance between consecutive punctual stimuli (e.g., a light pulse, or a tap) in a sequence is perceived as longer when the time interval from one stimulus to the next is longer [9]. Complementary, in the Kappa effect, the elapsed time between consecutive sensory stimuli presented at different locations is perceived as longer when their the spatial distance is larger [10]. To summarize, in Tau effect, the equidistance perception is modified by time, whereas in Kappa, isochrony perception is modified by space. Although several studies have already been presented regarding the Tau and Kappa illusions in multimodal conditions (e.g. audio-visual [11], audio-tactile [12]), no studies have reported an extensive comparison across different perceptual domains, nor the visual-tactile domain has been investigated yet. This investigation is of paramount importance to lay down the foundations for future multimodal stimulation paradigms in XR, which could be used for the customization of VR for clinical treatments, and the improvement of the effectiveness of user’s emotional elicitation in advanced human-machine and human-robot interaction [13], [14].

As a first step toward this ambitious goal, in this paper we developed a wearable device for visual and tactile stimulation for the evaluation of both Tau and Kappa effects, using a shared experimental procedure in the visual-tactile domain. Participants were asked to measure spatial and temporal intervals marked by sequences of three stimuli produced by a wearable device at the forearm. In particular, the perceptual effects studied in the unimodal conditions (i.e., only-visual, or only-tactile) were compared with the effects generated by different combinations of bimodal stimuli: visual and tactile stimuli were delivered both in a congruent fashion, or providing the perceptual bias only in one sensory channel at the time. Results show that both Tau and Kappa effects are affected by the multi-modality of the stimulation, and that the perceptual bias differently affected time- or space- perception based on the modality used for the stimulus delivery. The direction of the stimuli was investigated, too, to identify its influence on the Tau and the Kappa effects in the peripersonal space [15].

A. Related work

The spatial and temporal perceptual illusions have been widely studied since the early decades of the past century. Many studies reported the Tau effect in visual [16], [17], tactile [9], [18], and auditory [19] domains, confirming the existence of the effect regardless the perceptual channel involved. Specularly, also the Kappa effect has been reported in visual [10], tactile [20] and auditory [21] domain. However, this effect was not always found in the tactile modality [22], [23]. By contrast, shared experimental procedures were seldom developed to perform direct comparisons among different perceptual channels [22], or to measure both the Tau and Kappa effects within the same perceptual domain [24].

Concerning the multisensory stimulation, several studies investigated Tau and Kappa illusions arising from the interaction between the auditory channel and other senses: for instance, *Kawabe et. al* [11] found a significant Tau effect in the visual domain induced by the manipulation of the temporal offset between auditory and visual stimuli. *Russo and Dell'Antonio* [12], instead, were able to reproduce the tactile Tau effect exploiting the auditory Oppel-Kundt temporal illusion (i.e., a subdivided time interval is perceived longer than a non subdivided one), confirming that also an *apparent* temporal dilation can alter the perception of physical spaces. Finally, despite the usual prevalence of the auditory domain in the perception of time, *Bausenhart et al.* [25] found a significant Kappa effect originated by a task-irrelevant visual stimulus on the estimation of auditory intervals duration.

All the above-mentioned studies mainly investigated the effects played by an orthogonal stimulation on one channel to another perceptual channel, thus not providing information relevant to the dimension where the illusory effect is observed [25], [11]. By contrast, our research makes use of more ecological *convergent* visuo-tactile stimulation, providing redundant information across different perceptual domains on the independent variable, either space or time, that actually determine the illusory effect on the other dependent variable, either time or space. This addresses the Tau and Kappa effects when both the stimuli occur at the same body site (e.g., the forearm or the hand). The convergent stimulation is expected to produce effects of cross-modal integration, which were never addressed by previous studies on Tau and Kappa effects.

II. Materials and Methods

A. Wearable device for visuo-tactile stimulation

We designed a wearable device capable to provide visual and tactile stimuli to five subsequent, evenly spaced, stimulation points of the forearm (distance 25 mm) replicating the schema presented in [26]. The device, showed in Fig 1,

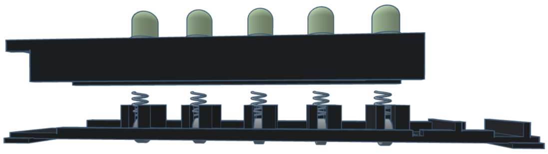

Fig. 1. 3D model of the wearable device

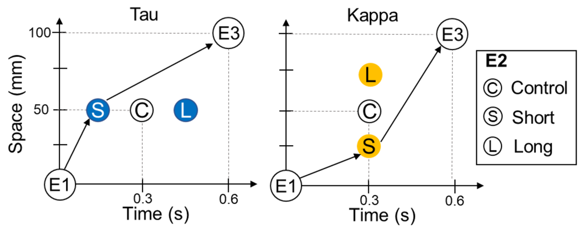

Fig. 2. Spatio-temporal scheme of the three stimuli (E1, E2, E3) provided in a trial for the Tau (left) and the Kappa (right) illusions. In each plot, the arrows show a trial having the first interval shorter than the second.

has a size of 200x20x25 mm (LxWxH), and is equipped on the top side with five high brightness LEDs (diam. 5mm, lum. 13 cd/m^2) covered by a black thin coating, aimed at hiding their exact position and number. In the bottom part, in correspondence with the LEDs, five round linear resonant actuators (LRA, mod.1027) are mounted so as to have their thinnest side in contact with the skin. The LRAs provide vibration stimuli at 140Hz with an amplitude of 1.5g. Each actuator is mechanically connected to the device by a 10 mm metal spring; thus, when the device is applied to the forearm, the vibration generated by each actuator produces a clearly localized tactile stimuli. The onset time and the duration of the stimuli are controlled by an Arduino Mega 2560 microcontroller connected to a laptop PC running Matlab R2021a.

B. Participants

Eleven subjects (5 males, 6 females) aged between 24 and 38 years (mean 28 y/o; standard deviation of 3.6 y/o) took part to the experiment. All participant were right-handed; none of them reported any visual or sensorimotor impairment. They participated on a voluntary basis and were not paid. The experimental protocol was approved by the Ethical Committee of the University of Pisa (Prot. n. 36590/2021).

C. Experimental procedure

The experiment adopted a widely used experimental design [9], [24] that provides the observer with three subsequent stimuli, designed to define two successive temporal intervals and two contiguous spatial intervals (see Fig. 2). Depending on the illusion under investigation (i.e., Kappa and Tau), the observer was then asked to compare the extent of two temporal or spatial intervals.

In each trial of the experiment, three successive stimuli (i.e., E1, E2, E3), lasting 75ms each [27], were delivered to the forearm along its distal-proximal axis. The total space $S = S^1 + S^2 = 100mm$ and the total time $T = T^1 + T^2 = 0.6s$ between the first (E1) and the third (E3) stimulus were always constant [26], [28], covering the entire length of the device. Instead, $S^1 = S_{E2-E1}$, $S^2 = S_{E3-E2}$, $T^1 = T_{E2-E1}$, and $T^2 = T_{E3-E2}$ were variable [9], [29]. Figure 2 shows the spatial and temporal interval combinations presented to the observers in the unimodal conditions. The trials conveying the Tau effect provided equal spatial intervals ($S^1 = S^2$) and different time intervals ($T^1 \neq T^2$) having a ratio of 1/3, 3/1, or 1/1 (Control). For each trial, the observer was asked to point the perceived spatial position of the second stimulus using an horizontal slider on a graphical user interface (GUI), thus defining two spatial extents. Conversely, the trials conveying the Kappa effect provided equal time intervals ($T^1 = T^2$) and different spatial intervals ($S^1 \neq S^2$): in this case, the observer was asked to evaluate the duration of the first time interval with respect to the second time interval using a vertical slider on the GUI. Trials were grouped in blocks sharing the dependent variable measured (i.e., time or space). In each block, the three interval ratios (1/3, 1/1 and 3/1) were replicated in two directions (i.e., distal-proximal, proximal-distal) resulting in 6 different combinations, each repeated 4 times. The resulting 24 trials in each block were fully randomized.

In the bimodal visual-tactile condition, all possible congruent and incongruent combinations were tested. Within congruent trials, visual and tactile stimuli were simultaneously provided at the same spatial locations: $S^i_{visual} = S^i_{tactile}$, $T^i_{visual} = T^i_{tactile}$. In the incongruent conditions, instead, one perceptual channel provided the illusion effect, whereas the other channel was unbiased (i.e., equal time and space intervals): $S^i_{visual} \neq S^i_{tactile}$, $T^i_{visual} \neq T^i_{tactile}$. Therefore, in the bimodal conditions there were: 6 congruent conditions (BC), same as in unimodal condition, 4 incongruent tactile conditions (BIT), in which the visual channel was unbiased ($S^1_{visual} = S^2_{visual}$, $T^1_{visual} = T^2_{visual}$) and the perceptual illusion was delivered via the tactile channel ($S^1_{tactile} \neq S^2_{tactile}$, $T^1_{tactile} \neq T^2_{tactile}$), and 4 incongruent visual conditions (BIV), as the inverse of the latter ($S^1_{visual} \neq S^2_{visual}$, $T^1_{visual} \neq T^2_{visual}$, $S^1_{tactile} = S^2_{tactile}$, $T^1_{tactile} = T^2_{tactile}$). Each combination was repeated 4 times, resulting in 112 trials. Similarly to the unimodal conditions, trials were randomized within blocks. In each trial, the observer was asked to judge both the visual and the tactile intervals using a GUI with two sliders, one for each perceptual domain. By using a within-subject design, the experiment evaluated in random order the unimodal visual and tactile conditions first, followed by the bimodal visual-tactile condition.

The experiment took place in a darkened room. Figure 3.a shows an observer wearing the experimental device fastened to his non-dominant forearm. We chose the dorsal part relaying on the results in [30]. In front of the observers, a LCD screen Asus VE247H provided a control GUI operated through the mouse. As shown in Fig. 3.c, observers were instructed to rest their arm on a support with the proximal-distal axis parallel and centered with respect to their chest;

Fig. 3. Experimental setup: a) observer's view of the device fastened to the dorsal part of the forearm, b) the bottom part of the device in contact with the skin, c) an observer simulating the experimental setup in normal light conditions.

this way, the spatial location of the stimuli was aligned to the horizontal axis of the screen. During the entire experiment, observers had to look at their forearm, whereas a continuous pink noise (approximately 65 dBA) was delivered through the earphones to mask any parasitic noise produced by the LRAs. Before the experiment, the observers performed a training phase using stereophonic auditory stimuli to familiarize with the experimental protocol and the different GUIs to be used.

D. Data analysis

In the analysis the categories belonging to the factor direction were named right-to-left (RL) and left-to-right (LR); the categories belonging to the factor interval ratio (either spatial or temporal) were named after the length of the first interval: long (3/1), short (1/3), equal (1/1).

For each factor combination, the variable *mean signed error* (MSE) was expressed, in percentage, as the mean difference between the slider position assigned by the observer and the real values in the respective trials. In order to assess the effects of the independent variables on the MSE, a separate non-parametric two-sided Friedman group-wise test for paired sample [31] was performed for each combination of the illusory effect to elicit (i.e., Kappa, Tau), perceptual domain (i.e., visual, tactile) and modality condition (i.e., unimodal, BC, BIV, BIT). Where significant differences emerged within a combination (i.e., within a subplot of Fig. 4, 5 or 6), then post-hoc pairwise comparisons were performed using non-parametric Wilcoxon test for paired samples [32], and p-values were adjusted for multiple comparisons through Bonferroni correction. Given the small sample size of this preliminary study (N=11), the statistical analyses were performed only on two factors, the interval ratio and the direction, to identify the presence of Tau and Kappa effect.

III. Results

A. Space evaluation

Figure 4 and 5 report the distributions of the spatial MSE for the factors temporal interval ratio and direction, respectively.

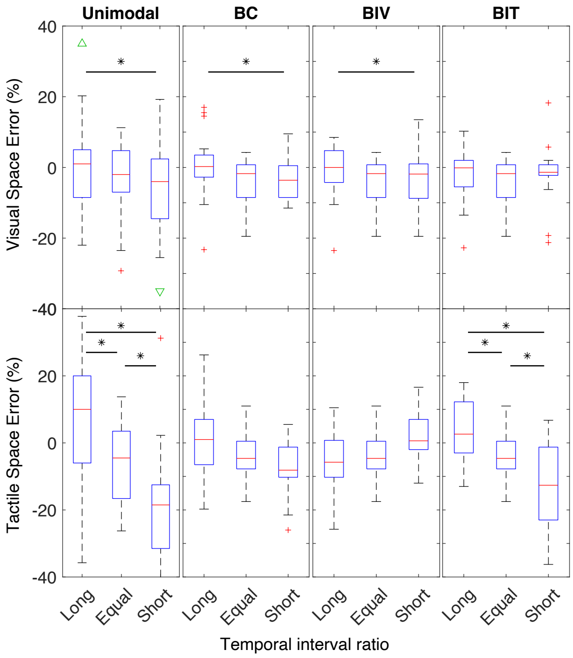

Fig. 4. Collection of boxplots reporting the spatial MSE for the factor interval ratio (Wilcoxon $* = p < .01$, Bonferroni corrected). The top-left subplot shows the direction of the theoretical Tau effect (green markers).

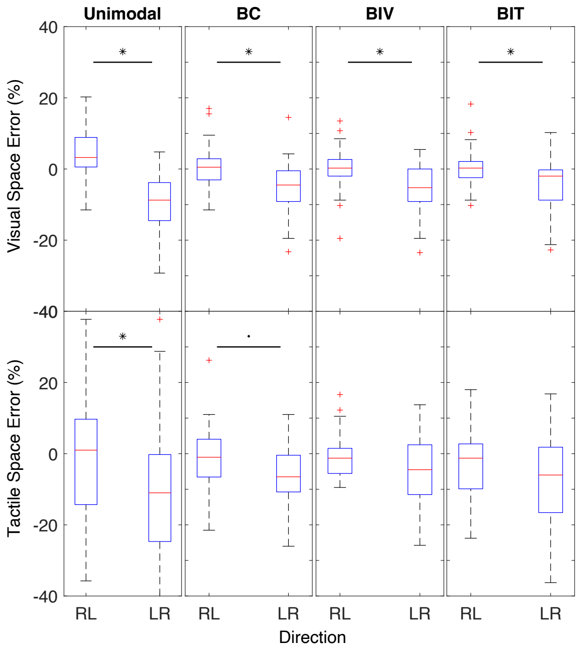

Fig. 5. Collection of boxplots reporting the spatial MSE for the factor direction. (Wilcoxon $. = p < .05, * = p < .01$)

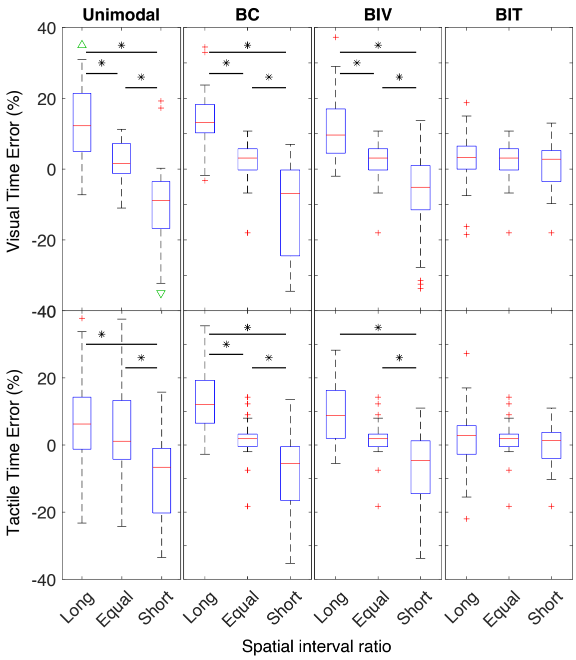

Fig. 6. Collection of boxplots reporting the temporal MSE for the factor interval ratio (Wilcoxon $* = p < .01$, Bonferroni corrected). The top-left subplot shows the direction of the theoretical Kappa effect (green markers).

1) Effect in the tactile domain: As shown in the bottom-left boxplot of Fig. 4, in the unimodal condition significant differences were detected between short, equal and long temporal interval ratios (Q=23.5, p<0.001). Pairwise comparisons revealed significant differences between long-equal intervals (Z=3.2, p<0.01), short-equal intervals (Z=-3, p<0.01) and long-short intervals (Z=3.4, p<0.01), confirming the Tau effect (i.e., short time interval results in underestimations of the physical space, and long time interval in overestimations). Statistically significant differences were detected in the tactile domain in the BIT condition (Q=20, p<0.001), with similar post-hoc differences between long-equal intervals (Z=2.9, p<0.01), short-equal intervals (Z=-3.5, p=0.001) and long-short intervals (Z=3.4, p<0.01). With respect to the stimuli direction (Fig. 5), the left-to-right (LR) direction was found significantly lower than the right-to-left (RL) direction in unimodal (Z=2.4, p=0.01) and BC (Z=2.3, p<0.05) conditions.

2) Effect in the visual domain: Regarding the factor temporal interval ratio (top row of Fig. 4), the statistically significant differences found in the unimodal condition (Q=12.1, p<0.01) were confirmed by the post-hoc analysis only for the long-short interval pair (Z=3.2, p<0.01); therefore, differences with the control condition were not significant. Analogously, significant differences found in BC (Q=7.9, p<0.05) and BIV (Q=8.3, p<0.05) conditions resulted in significant pairwise comparisons only for their long-equal interval pairs: (Z=3.3, p<0.01) and (Z=3, p<0.01), respectively.

The direction of stimuli (Fig. 5) was found statistically significant in all the conditions: unimodal (Z=4.6, p<0.001), BC (Z=2.8, p<0.01), BIV (Z=3.1, p<0.01), and BIT (Z=2.6, p<0.01).

B. Time evaluation

Figure 6 reports the distributions of the temporal MSE for the factors spatial interval ratio.

1) Effect in the tactile domain: In the unimodal condition statistically significant differences were detected ($Q=17.8$, $p<0.001$). However, pairwise comparisons revealed significant differences only between short-equal intervals ($Z=-3.4$, $p=0.001$) and long-short intervals ($Z=3.6$, $p=0.001$). Significant differences were detected also in BC ($Q=23.3$, $p<0.001$) and BIV conditions ($Q=13.7$, $p=0.001$). Pairwise comparisons in BC case revealed significant differences between long-equal intervals ($Z=3.6$, $p<0.001$), short-equal intervals ($Z=-3.6$, $p<0.001$) and long-short intervals ($Z=3.7$, $p<0.001$). In BIV condition, instead, differences were significant for short-equal intervals ($Z=-3.2$, $p<0.005$) and long-short intervals ($Z=3.3$, $p<0.005$).

2) Effect in the visual domain: In the unimodal condition, statistically significant differences were detected ($Q=26.5$, $p<0.001$). Post-hoc comparisons revealed significant differences between long-equal intervals ($Z=3.4$, $p<0.005$), short-equal intervals ($Z=-3.2$, $p<0.005$) and long-short intervals ($Z=3.7$, $p<0.001$), confirming the Kappa effect. Significant differences were detected in BC ($Q=18.6$, $p<0.001$) and BIV ($Q=14.1$, $p<0.001$) conditions where the post-hoc comparisons had similar differences ($p<0.01$).

Regarding the direction, no significant differences were observed in both the perceptual domains.

IV. Discussion

The experimental results revealed that the designed wearable device is able to generate Tau and Kappa effects in unimodal conditions. However, the magnitude of the effects depended on the perceptual domain involved: in the tactile domain, a clear Tau effect was found in accordance with the literature [9] as well as the Kappa effect [20] (of note the Kappa effect was not consistently reported in the tactile modality [23], [22]). In the visual domain, although a clear Kappa effect was found [10], the Tau effect was only seldom significant (i.e., in the long-short pair). This might be explained by the higher spatial discrimination of vision over touch [33]; since the comparison of the illusions based on bounded physical distances was one of the aims of our study, this result shows the limits of the Tau effect in the peripersonal space in the visual domain.

The direction of the stimuli was significant in the space estimation, especially concerning the visual domain, as the LR direction resulted always in underestimations of the space (see Fig. 5). Since the approaching stimuli (i.e., looming) induce a dilation of subjective duration, and the receding ones induce the opposite effect in vision and audition [15], we speculate that the LR direction produced a receding effect with consequent space underestimations. This is a remarkable result of this study, since previous investigations, having the visual stimuli delivered outside the peripersonal space, showed that the direction was not significant [17], [24]. Regarding the estimation of time, instead, no effects on direction were identified [10].

Compared to the previous studies on multimodal stimulation [25], [11], [12], each assessing only a specific incongruent condition, this study provides a wide overview, although on a preliminary base, of all the possible reciprocal influences between visual and tactile domains concerning time and space perception. This overview shows a general preeminent role of the visual domain on the tactile one, specially when they conflict [34]: in particular, regarding the time perception, the Kappa effect vanished in both the perceptual channels when the temporal illusion was provided in the tactile domain only (i.e., BIT). In this regard, the higher spatial discrimination thresholds of other body parts (e.g., the palm) [35] can result in a stronger Kappa effect, and possibly different multimodal integration. Regarding the space perception in the tactile domain, instead, the isynchrony between visual and tactile stimuli delivered in BIT and BIV conditions led to the perception of shorter spatial extents when the visual stimulus preceded the tactile one, and vice versa (see Fig. 6). Therefore, in the perspective of future applications in VR, the asynchrony between visual and tactile stimuli can be potentially used to alter the space perception in the tactile domain.

Most importantly, the delivery of multimodal congruent visual-tactile stimuli (i.e., BC condition) did not cancel the Tau and Kappa illusions as expected by the optimal integration of these modalities [33]. Conversely, the visual-tactile congruent stimulation slightly increased the Kappa illusion in the BC condition with respect to the unimodal conditions. In this regard, the illusory effects found in this study in the visual and the tactile domains are expected to increase in VR, as the perceptual priors experienced in the real world can be strongly biased concerning both the modalities [8]; moreover, the visual-tactile crossmodal integration could improve the sense of immersion and the customization of the experience [36].

Main limitations of this work might be related to the low number of participants, and the specific stimulation deployment. Indeed, it is authors' belief that Tau and Kappa effects might be improved by delivering the visual stimuli in regions far from the fovea [37], which should be enhanced in XR environment.

V. Conclusions

This study investigated the presence of Tau and Kappa effects when they are originated on the same body site through convergent visual and tactile stimuli, using a shared experimental protocol. This preliminary experiment confirmed the existence of Tau and Kappa effects in both perceptual channels in unimodal conditions. Most importantly, results showed the persistence of the illusions also in the bimodal congruent conditions and a dominance of the vision on the tactile domain when they conflict. Taken together, these preliminary results suggest promising outcomes in the perspective replication of the Tau and Kappa visuo-tactile illusions in XR: in fact, in virtual environments the constraints of the human body (e.g., arm length) can be violated thanks to a modified visual representation of the limbs supported by coherent tactile stimulation [8]. Furthermore, such multimodal stimulation can boost the sense of immersion, shifting the peripersonal space to the representation of self in VR [7]. This may elicit affective responses that could be used in clinical treatments or for advanced social human-robot interaction [38].

Future works will envision a deep investigation of Tau and Kappa effects in multimodal conditions, considering also different temporal and spatial extents to estimate the magnitude and the maximum boundaries of such effects through psychometric functions. A Bayesian modelling of the effects across the visual and tactile channels is also envisioned [33], [26]. To this end, the modeling of the spatial and temporal illusions elicited by multimodal visuo-tactile feedback in the real world will allow the validation of these effects for an effective translation in XR, which is the final aim of our research. Our goal is to use the here reported results to induce distortions in the self perception in the time and spatial domain, capitalizing on a multimodal stimulation to enhance users' immersiveness.

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