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Investigating the Kappa Effect elicited through concurrent visual and tactile stimulation

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The experience of time and space in subjective perception is closely connected. The Kappa effect refers to the phenomenon where the perceived duration of the time interval between stimuli is influenced by the spatial distance between them. In this study, we aimed to explore the Kappa effect from a psychophysical perspective. We investigated participants' perception of temporal duration in the sub-second range by delivering visual and tactile inputs through wearable devices placed on both the palm and the forearm. We compared the impact of unimodal sensory stimulation, involving either visual or tactile stimuli, with different bimodal stimulation conditions. Our results revealed that the illusory effect on inter-stimulus duration perception can be observed in both unimodal conditions, although the distortions were significantly more pronounced in vision. In the multimodal stimulation condition, where visual stimuli were presented at non-equidistant spatial locations, the integration of tactile input did not reduce the Kappa effect, regardless of the spatial location of the tactile stimuli. However, when the visual stimuli were equidistant in space, regardless of the spatial location of the tactile stimuli, the Kappa effect disappeared. These results can shed light on the effect played by multimodality on the perception of space and time.

***Index Terms*—Kappa effect, time perception, space perception, multimodal stimulation, vision, touch**

I. Introduction

In humans there are clear inter-dependencies in the perception of time and space [1], [2]. Such inter-dependencies have been investigated in several studies, using different stimulation modalities such as visual, auditory and tactile, with experimental outcomes that were highly modality and task-dependent [3], [4].

Paradigmatic examples are the so called *Tau and Kappa* effects. In the Tau effect the perception of the distance between two or more consecutive stimuli is influenced by the duration of the inter-stimulus temporal interval [1]. In the Kappa effect, the perception of the duration of the inter-stimulus interval between two or more consecutive stimuli is influenced by the physical distance between them (i.e. the perception of isosynchrony is modulated by space: the greater the spatial inter-stimulus distance, the longer the inter-stimulus temporal interval is perceived, and vice-versa [2]). Although the exact origin of these perceptual space-time distortions is still debated, the most discussed theories attribute them to the violation of participants' prior information, which is triggered by the apparent motion of the stimuli. Previous works identified the prior in terms of speed constancy [5]. A Bayesian framework proposed by [6] assumed a slow speed prior, indicating that humans tend to associate slow motion with real-world objects. Finally, a recent study [7] suggests that the deceleration tendency in the space-time perception is the result of the Weber-Fechner law.

In this work, we focused on the study of the Kappa effect, which - compared to the Tau one - was demonstrated to be more consistently elicited across perceptual modalities, although with different magnitudes according to the type of stimulation. This was also confirmed in a previous preliminary work of our group [8], where we analyzed both the Kappa and the Tau effect elicited through concurrent visual-tactile stimulation. We found that the Tau effect was seldom elicited, especially in the visual modality, in agreement with other recent findings in literature [9].

A. Related work

In the visual domain, the Kappa effect was studied using different experimental protocols, and reported by several authors [2], [10], [11]. In the auditory domain, pitch space model was proposed to account for the Kappa effect by relating low frequencies tones to long time intervals and high frequencies tones to shorter time intervals [12]. A Kappa effect was also found in a stereophonic scenario, where the inter-stimulus time (IST) was perceived longer when it was elicited along different directions (i.e., right-left or left-right) than along the same direction (i.e. left-left or right-right) [13].

In the tactile domain, the evidence of the Kappa effect has been rarely reported. Suto [14] demonstrated the existence of a Kappa illusory effect by alternately stimulating participants' forearms through consecutive tactile stimuli. With the forearms crossing each other, different apparent spatial distances between tactile stimuli were considered. Grondin *et al.* [15] showed that the temporal duration of consecutive tactile stimuli, which were delivered on different hands (i.e., left-right or right-left), was perceived to be longer compared to the same perception elicited by tactile stimuli on the same hand (i.e., right-right or left-left). However, partially in contrast

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with [14], the increase in inter-hands physical distance did not affect the perceived duration. Yoblick *et al.* [12] found no relation between the frequency of the tactile vibration and the perception of its duration. Finally, Hidaka *et al.* reported that the inter-stimulus interval between two tactile inputs was overestimated when the stimuli were presented longitudinally on the dorsum of the hand as compared to horizontally [16]. In summary, to the best of our knowledge, a consistent Kappa effect (i.e. a proportional relation between spatial distance and temporal judgment distortion) has not been demonstrated in the tactile domain, particularly when considering contiguous areas of the same body site (e.g., the forearm, the palm). Speculatively, as suggested by Goldreich [6], this might be due to the poor spatial accuracy of the body site tested compared to the distance of the stimuli provided (i.e., skin stimulation areas within the two-point-discrimination threshold [17]).

The Kappa effect elicited by multiple stimulation modalities has received even less attention. Bausenhart *et al.* [18] found a significant Kappa effect on the temporal estimation of auditory intervals, which was elicited through visual stimulation. The same authors induced a perceived time dilation by modulating the asynchrony between visual and auditory stimuli [19]. Interestingly, a quasi-optimal temporal integration, in the Maximum Likelihood Estimation (MLE) sense, of the two sensory channels was observed, when the attention of participants focused on the visual domain. In other terms, the computed Just Noticeable Difference (JND) was significantly lower in the bimodal (audio-visual) stimulation condition than in the unimodal visual condition, confirming that the channel with lower variance in the temporal domain, i.e. audio, leads the cross-modal integration process [20].

Only a few studies have investigated the Kappa effect and the spatio-temporal perception across visual and somatosensory (i.e. tactile) domains. Asai et al. [21] investigated the *Rabbit illusion* in multimodal conditions finding that concurrent signals from the visual modality provides clues for creating unified representations of the tactile apparent motion (multimodal causality). Cai et al. [3] performed experiments where participants were asked to report on the length of physical sticks or the duration of an auditory note, which was listened to during the interaction with the sticks. When the latter was mediated by both the visual and tactile channel, length and duration judgments were influenced by each other in a similar fashion (this did not happen when visual cues were not delivered). This was explained by the high spatial acuity of vision that drove the space-time interaction.

The spatiotemporal processing across vision and touch was also investigated in the context of apparent motion [22], [23]. In this case, a clear dominance of the visual channel was reported e.g. by Lyons *et al.* [24] and Craig [25] as the perception of the tactile stimuli direction was manipulated by exploiting the spatial congruence of visual stimuli delivered at the same time. However, these studies did not explicitly target the identification of a relation between the spatial distance of the delivered stimuli and the magnitude of the elicited effect on the inter-stimulus temporal perception.

B. Implications for Extended Reality

Besides the scientific interest in investigating possible integration strategies across visual and tactile domains for spatio-temporal perception, our main goal is the exploitation of the Kappa effect with concurrent visuo-tactile stimulation in advanced human-machine interaction. In this regard, this study was designed in the context of the Experience Project [26]: one compelling yet challenging translation of the results of the project is the design of strategies for multimodal manipulation of time perception in extended reality (XR), e.g. to advance current clinical psychology procedures. In fact, XR has proved its effectiveness in several psychological treatments, giving rise to what it is known as *Virtual Reality Exposure Therapy* (VRET) [27]. This type of therapy allows for the creation of a safe virtual world where the patient can experience new realities also relying on perceptual illusions [28]. The investigation of the Kappa effect we targeted goes toward this direction, i.e. the creation of a compelling virtual multimodal reality environment for the manipulation of time perception.

In a first preliminary study, we investigated the interaction between the visual (V) and tactile (T) domain for the elicitation of the Kappa effect on the forearm through visuo-tactile stimuli [8]. More specifically, we provided participants with three consecutive stimuli, which were designed to define two successive temporal intervals and two contiguous spatial intervals. We studied the Kappa effect both in the unimodal conditions (i.e., only-visual, or only-tactile) and with different combinations of bimodal stimuli: visual and tactile stimuli were delivered both in congruent combinations (i.e. in the same location) or in incongruent combinations (i.e. one sensory channel provided uneven spatial intervals while the other provided equal spatial intervals). We found a preeminent role of the visual domain over the tactile one, due to the fact that vision is associated with higher spatial resolution (i.e. less sensory variance) than touch. Consistent with this, we found that the Kappa effect vanished in both the perceptual channels when the temporal illusion was provided in the tactile domain only. On the contrary, the visual-tactile congruent stimulation slightly increased the Kappa illusion. These results, although promising, were preliminary, considering that our investigation suffered from some limitations. These can be mainly ascribed to the number of stimuli we delivered and the target location for the stimulation.

In a second study [29] we also investigated the Kappa effect in VR by testing unimodal visual and visual-tactile congruent stimuli only on the forearm. Results in VR were compared with a subset of the results presented in this manuscript (i.e. unimodal and visual-tactile congruent configurations) showing that the Kappa effect can be successfully elicited also in the VR environment.

In this work, we detail a comprehensive characterization of the link between time perception and multimodal visual-tactile conditions, both on the forearm and the palm, as they hold significant promise for eliciting desired effects in XR. In particular, we considered different temporal and spatial extents to estimate the magnitude and the maximum boundaries of the Kappa effect through psychometric functions. As shown

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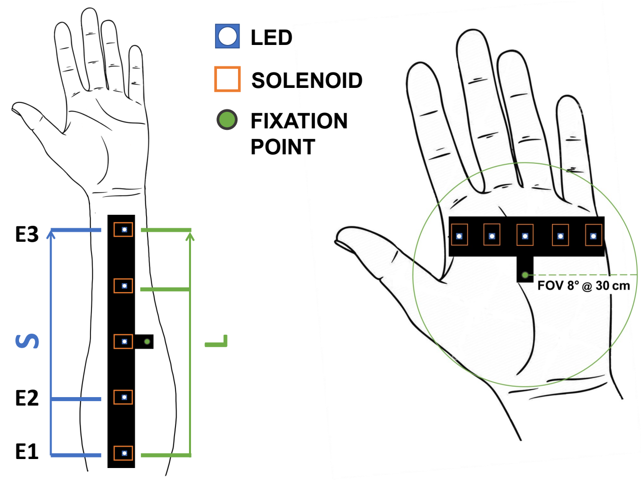
in Fig. 2, for each factor (and combinations thereof) we fitted individual psychometric functions by evaluating seven complementary Inter Stimulus Intervals (ISTs). Combined factors included the spatial distributions of stimuli, the modality (i.e. visual (V), tactile (T), bimodal congruent (BC), bimodal incongruent visual (BIV) and bimodal incongruent tactile (BIT)) and the body site (i.e., forearm and palm). Besides testing the presence of the Kappa effect with multiple combinations of IST with different duration, this study investigates the Kappa effect elicited by bimodal stimulation with congruent or incongruent spatial information to provide a thorough characterisation of the effects of the visual-tactile crossmodal integration concerning the temporal [19] and the spatial [20] domains for the elicitation of the Kappa effect. Humans are able to integrate congruent visual and tactile information in a statistically optimal fashion [20]; however, when the stimuli are not congruent (i.e., not interpreted as a unique percept), the brain may apply different integration or segregation strategies to optimize the statistical inference [30], [31].

We hypothesized that the sensory modality with the greatest spatial acuity - that is the one with lower variance in the spatial domain, i.e. the vision, should drive the Kappa effect when the stimuli are not spatially congruent, as suggested by our preliminary work and other previous findings [3], [24], [25]. Finally, we also investigated the relationship between the magnitude of the Kappa effect and the temporal discrimination thresholds of each participant. Our hypothesis was that this relation relies on the cross-modal integration between vision and touch, within both the spatial and the temporal domain, considering the sensory variance of vision and touch for both time and space perception. The characterisation of the Kappa effect through the computation of individual psychometric functions was motivated by the need for devising quantitative tools that can be used, in the future, to calibrate and tune the XR-enabled manipulation of time perception in a participant-specific fashion.



(a) Experimental devices

(b) Setup of the experiment

Fig. 1: Top: wearable devices used in the experiment. The forearm device exemplifies the stimuli sequences short(S) and long(L) while the palm device reports the field of view perceived at a distance of 30 cm. Bottom: setup of the experiment (the participant is looking to the fixation point).

II. Methods

A. Participants

Fifteen right-handed participants (10 males and 5 females, M=31.7, SD=5.9) took part in the experiment. They participated on a voluntary basis and were not paid. Each participant reported normal or corrected-to-normal visual acuity and no sensorimotor impairments. Informed consent was obtained prior to participation. The experimental protocol was approved by the Ethical Committee of the University of Pisa (Prot. n. 36590/2021); the experiment and all methods were performed in accordance with the relevant guidelines and regulations.

B. Hardware

We designed two wearable devices, which can deliver tactile and visual stimuli to the forearm and the palm. Figure 1(a) shows the schematics of forearm and palm devices, having a size of $200 \times 22 \times 35\ mm (L \times W \times H)$ and $88 \times 22 \times 35\ mm$, respectively. Each device provided five consecutive, evenly spaced stimulation points whose distance was selected to be substantially higher than the two-point-discrimination tactile thresholds [32], [33]; the selected distances were 42 mm for the forearm and 14 mm for the palm.

Furthermore, each device provided a visual fixation point placed at the center, at a distance of 24 mm perpendicularly to the stimulation direction (participants were asked to look at the fixation point during each trial). The tactile stimuli were delivered by 5 V push-pull solenoids driven by independent power circuits [34]. The visual stimuli were delivered through a series of $WS2812$ LEDs (white color) whose positions were in correspondence with those of the solenoids. The onset time and the duration of the stimuli were controlled by an Arduino Mega 2560 microcontroller connected to a laptop PC running Matlab R2021a (MatLab Inc., USA). To ensure a precise temporal control of the stimuli, each trial of the experiment was managed by the microcontroller timers. Temporal synchronization and stimuli duration were measured by comparing the microcontroller digital output signal of the LEDs with the recordings of a ADXL327Z accelerometer (attached to a test surface in a position almost equidistant to the tactile actuators) on repeated measurements. Maximum time mismatch was always under 1.2 ms.

C. Stimuli and procedure

The experiment followed a within-subject design: all participants tested all factor combinations of space, IST, modality and place. The experiment was divided into two sessions with the same procedure, one for the forearm and one for the palm. The order of the sessions was counterbalanced across participants. Sessions were interleaved by 7 to 10 days.

The experiment adopted a widely used experimental procedure [1], [35] that provides the observer with three consecutive stimuli (E1, E2, E3), designed to define two successive temporal intervals (T^1, T^2) and two contiguous spatial intervals (S^1, S^2), see Fig. 2 and 1a. Independently from the space existing between the stimuli, the observer was asked to compare the duration of the two temporal intervals following a two-alternative forced-choice (2AFC) protocol.

In each trial of the experiment, three successive stimuli (E1, E2, E3) either visual (V), tactile (T) or visual-tactile (VT), were delivered to the forearm or to the palm depending on the session. The duration of the stimuli was 47 ms [10], [11]. The total time $T = T^1 + T^2$ between the first (E1) and the third (E3) stimulus was always equal to 600 ms; within each session, also the total space $S = S^1 + S^2$ between the first (E1) and the third (E3) stimulus was constant: 56 mm for the palm, and 170 mm for the forearm, respectively [6], [36]. The spatial intervals $S^1 = S_{E2-E1}$ and $S^2 = S_{E3-E2}$ were varied [2]. Figure 2 shows the possible combinations of complementary spatial intervals presented to the observers given equal time intervals lasting 300 ms each: the trials conveying the Kappa effect provided different spatial intervals ($S^1 \neq S^2$) having a ratio between the first and the second interval of 1/3 (Short) or 3/1 (Long). Conversely, the trials conveying the Control condition provided equal spatial intervals ($S^1 = S^2$).

According to the 2AFC protocol, seven combination of IST $T^1 = T_{E2-E1}$, and $T^2 = T_{E3-E2}$ with increasing differences were provided to the observer, see Fig. 2; in one combination the IST was the same, and equal to 300 ms. The minimum difference between temporal intervals was selected to be 60 ms based on published thresholds [37], and the maximum difference was selected to be 180 ms, to ensure a sufficient discrimination in both the modalities [38]. Each of the seven time intervals was repeated 20 times for each factor combination.

Trials were grouped in 13 blocks sharing the factor Modality (i.e., V, T, VT). Within each block 140 trials were fully randomized. Both the unimodal conditions V and T provided the observer with: 3 space ratios × 7 time intervals × 20 repetitions = 420 trials. In the bimodal condition (VT) stimuli were always synchronized in time. Regarding the space, the VT condition provided also incongruent trials where one perceptual channel provided the Kappa effect, whereas the other channel provided the control condition (i.e., equal space intervals). Therefore, in the bimodal conditions there were: 420 congruent trials (BC), same as in unimodal condition, plus 280 incongruent tactile trials (BIT), in which visual stimuli were delivered to identify two spatially equivalent intervals - control condition ($S^1_{visual} = S^2_{visual}$) and the tactile stimuli were delivered to identify two different spatial intervals (either S or L condition) ($S^1_{tactile} \neq S^2_{tactile}$), plus further 280 incongruent visual conditions (BIV), as the inverse of the latter ($S^1_{visual} \neq S^2_{visual}$, $S^1_{tactile} = S^2_{tactile}$). Since the direction of the stimuli sequence was proven to not affect the Kappa effect [2], [11], it was set constant for each device: left-to-right on the palm, in a distal to proximal direction on the forearm. Therefore, in total each participant performed 1820 trials for each session, 3640 in total.

The experiments took place in a quiet room. Figure 1b shows an observer wearing one of the experimental devices fastened to the non-dominant hand (according to the literature [39], the multi-sensory integration is enhanced in the non-dominant hand). Participants were asked to place their arm on the support (tilt 60°) keeping their forehead on the headrest by adjusting the height of the chair: this way the distance between the eyes and the LEDs on the devices was kept constant at 30 cm. As a reference, Fig. 1a reports also the 8° Field Of View (FOV) from the fixation point at a distance of 30 cm, the area where the visual Kappa effect was found at its maximum extent [11].

During the experiment, participants wore ear-plugs while a continuous pink noise (approximately 70 dBA) was delivered through earphones to mask any parasitic noise produced by the solenoids. Each experimental block was started by an LCD screen showing the next modality (i.e., V, T, VT) to the participant. In each trial, participants had to choose the *shortest time interval* pressing the left or the right arrows on a keyboard placed nearby the arm support. The next trial started $700 - 900$ ms after a response was recorded.

Before the experiment, to familiarize with the experimental procedure, participants performed a training phase of 48 trials on all the modalities with time intervals of 150 ms and 450 ms, respectively. The experimenter checked that participants were able to distinguish the two intervals and that they clearly understood the task. Participants were allowed to rest between blocks at their convenience. A typical session lasted 1.5 hours.

III. Results

For each participant, the responses of the 2AFC discrimination task were modeled as a psychometric function for each factor combination of place (forearm, palm), space covered by the first interval (short, equal, long, corresponding to S, C, L condition, respectively) and modality (i.e., V, T, BC, BIV, BIT) by fitting a cumulative Gaussian function with two free parameters: midpoint μ, and standard deviation σ. Given such parameters, it was possible to estimate the two main variables of standard psychophysical analysis: the point of subjective equality (PSE) as the midpoint, and the just notable difference (JND), calculated as $\sqrt{2 * \sigma^2}$ by following the procedure reported in [40].

The parameters of the psychometric functions fitted for each participant were used in the statistical analysis. Since the individual distributions of PSE and JND were not normally distributed (i.e. D'Agostino normality tests were performed

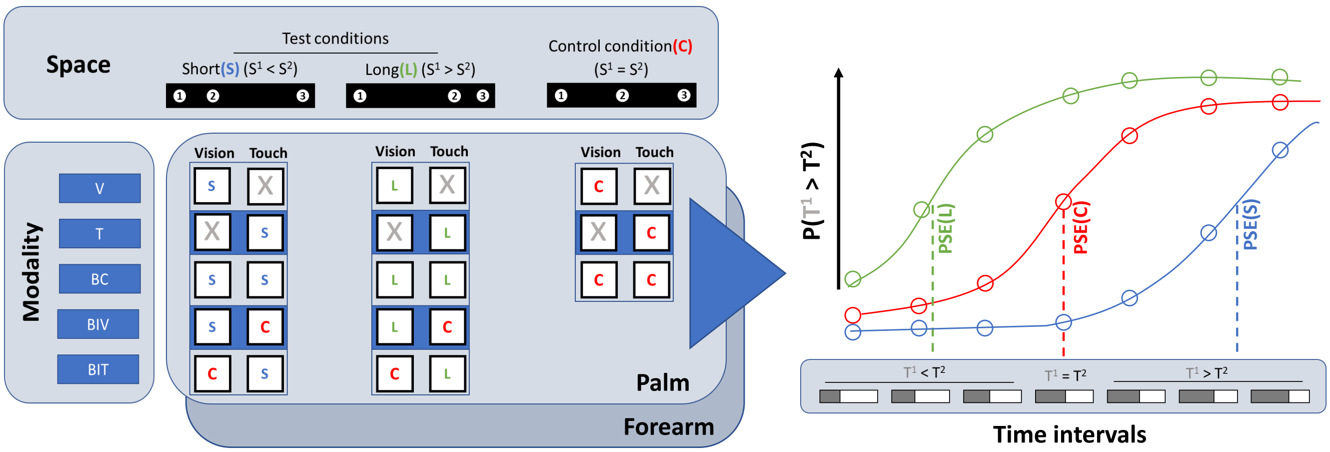


Fig. 2: left: the factors combinations (Space, Modality, Place) tested in the experiment. Right: the expected Kappa effect reported in three representative psychometric curves, which results in a shift of the point of subjective equality (PSE) in the S (contraction of the perceived temporal distance between stimuli) and L (dilation of the perceived temporal distance between stimuli) spatial conditions with respect to the PSE in the control condition (C). The psychometric curves were evaluated across seven complementary IST having increasing duration differences of 60 ms.

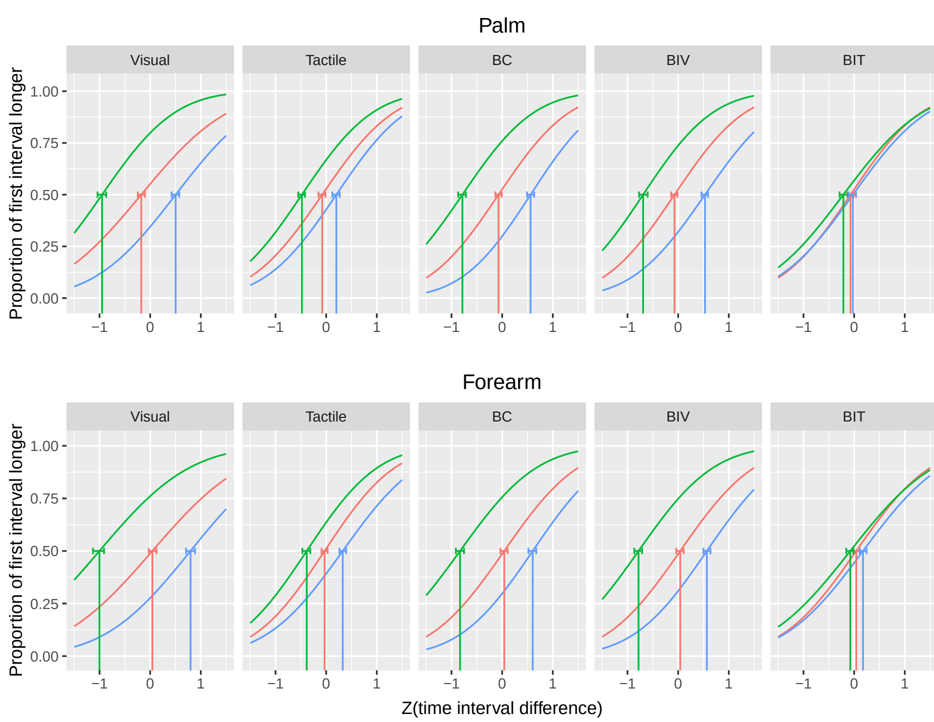


Fig. 3: Psychometric functions calculated at the group level for all factor combinations. The differences between the seven time interval durations were z-transformed. Red lines indicate equal intervals (control condition), blue lines indicate the first interval long, and green lines indicate the first interval short.

TABLE I: Difference in PSE due to the factor Space for all Modalities on the Forearm Significance levels: .=0.05, *=0.01, **=0.001, ***=0.0001 with Holm correction

Test	**Visual**	**Tactile**	**BC**	**BIV**	**BIT**
Friedman	Q=26.5 (***)	Q=19.2, (***)	Q=28.1, (***)	Q=28.1, (***)	Q=7.6, (.)
Wilk. (Long-Short)	***	***	***	***	.
Wilk. (Long-Equal)	***	**	***	***	.
Wilk. (Equal-Short)	***	**	***	***	.

TABLE II: Difference in PSE due to the factor Space for all Modalities in the Palm Significance levels: .=0.05, *=0.01, **=0.001, ***=0.0001 with Holm correction

Test	**Visual**	**Tactile**	**BC**	**BIV**	**BIT**
Friedman	Q=24 (***)	Q=22.9, (***)	Q=19.2, (***)	Q=18.1, (***)	Q=5.6, (.)
Wilk. (Long-Short)	**	**	**	**	.
Wilk. (Long-Equal)	**	**	**	**	–
Wilk. (Equal-Short)	**	.	**	**	–

[41] finding mainly violation of the skewness on distributions), non-parametric group-wise Friedman tests for paired samples [42] were performed. Therefore, whenever significant differences emerged, post-hoc pairwise comparisons were performed using non-parametric Wilcoxon test for paired samples with Holm correction [43]. Further modeling of the Kappa effect by means of generalized linear mixed models (GLMM) can be found in the appendix. Data were analysed using the software R 4.1.2 using $Quickpsy$ [44] and $MixedPsy$ [45] package.

Figure 3 reports the overall group mean psychometric functions calculated for all combinations of place, space, and modality factors. The differences of time interval durations were z-transformed as required by the statistical analyses. The PSE of the psychometric functions increases or decreases due to the space factor according to the Kappa effect: longer spatial intervals result in time dilation and vice versa. Of note, a larger PSE corresponds to a shorter perceived duration of the first interval, while the PSE is close to zero in all the control conditions with equally-spaced intervals (red lines in Fig. 3) independently from the modality and place factors. A PSE close to zero in the control condition accounted for a correct temporal discrimination of equidistant stimuli, therefore confirming the absence of systematic biases in determining the longest time interval.

A. Kappa effect

As reported in Table I and II the Friedman's test on the PSE revealed highly significant differences across the space factor (i.e. $p < .0001$) for each combination of modality and place, except for the BIT modality ($p < .05$). The differences among PSE were confirmed by a post-hoc pairwise comparison, showing $PSE_{long} < PSE_{equal}$, $PSE_{equal} < PSE_{short}$ and $PSE_{long} < PSE_{short}$ according to the Kappa effect for all combinations except the BIT modality in the Palm. In order to quantify the magnitude of the Kappa effect, we computed the difference between the PSEs in the short (S) and long (L) spatial intervals. This, in turn, provides an overall estimation of the perceptual alteration induced by different spatial distribution of isosynchronous stimuli.

Figure 4 illustrates the boxplots of the magnitude of the Kappa effect for all the stimulation modalities presented on the forearm and the palm. Regarding the forearm, the Friedman test for paired samples showed significant differences among modalities ($Q = 29.4$, $p < .0001$). Post-hoc pairwise comparisons for paired samples considering the visual modality in a one-to-many comparison revealed significant differences between visual and tactile modalities ($p < .05$) and between visual and BIT modalities ($p < .05$).The differences between visual-BC and visual-BIV were not significant ($p = .24$ and $p = .12$ respectively) Regarding the palm, the Friedman test showed significant differences among modalities ($Q = 33.7$, $p < .0001$). Again, the post-hoc pairwise comparisons revealed significant differences between visual and tactile modalities ($p < .05$), and between visual and BIT modalities ($p < .05$). The differences visual-BC and visual-BIV were not significant ($p = .27$ and $p = .09$ respectively)

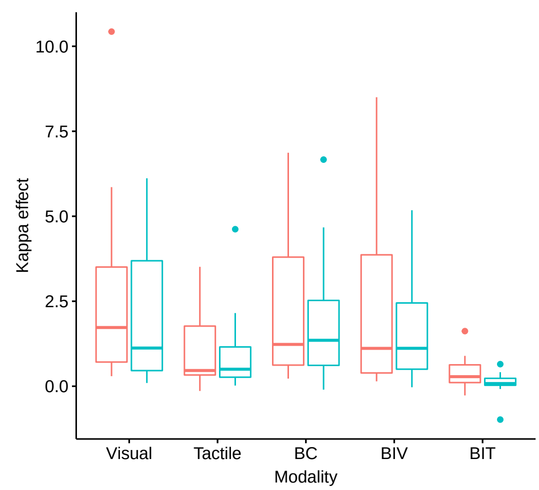


Fig. 4: Magnitude of the Kappa effect for all factor combinations of Modality and Place. The Kappa effect was calculated from z-transformed time intervals. Colors: red indicates the forearm, blue the palm.

B. Duration discrimination

The JND of the psychometric curves indicates the participants' ability to discriminate the temporal duration of

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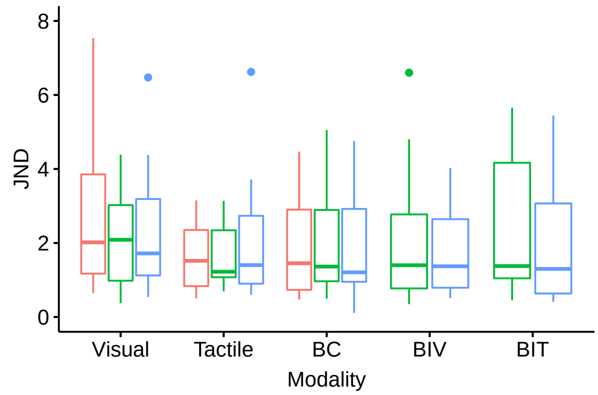
different intervals: the lower the JND, the higher the ability. Figure 5a and 5b show the boxplot of the JND grouped by modality and space for the forearm and the palm, respectively. Separate Friedman tests were performed for the factors Space and Modality.As shown in Table III, in all the stimulation modalities the factor Space was found not significant both on the palm and the forearm. Table IV reports the differences in JND due to the factor Modality, which was found significant only in the control condition, with equal spatial intervals. In this condition, the post-hoc comparisons revealed a statistically significant higher JND for the visual modality with respect to both the tactile and the BC modalities ($p < .0167$) on the forearm; in the palm differences were significant only between the visual and the BC modality ($p < .0167$).

For each participant, the JNDs measured in visual and tactile modalities were used to estimate the expected discrimination thresholds in the BC modality following the optimal integration according to the MLE rules [40], which are described by the equation 1.

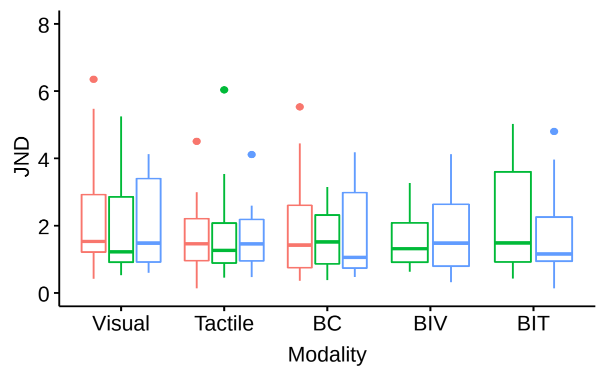
$$T_{VT}^2 = \frac{T_V^2 T_T^2}{T_V^2 + T_T^2} \tag{1}$$

The estimated discrimination threshold in multimodality (T_{VT}) is calculated from the discrimination thresholds (T_V and T_T) found in the unimodal Visual and Tactile modality. According to it, the perceptual channel having the lowest variance in unimodal condition or the highest acuity in the time domain (i.e. the tactile channel in our case) has a greater weight in estimating the discrimination threshold in the multimodal condition. The theoretical estimation of the thresholds was then compared with the experimental thresholds.

Figures 6a and 6b show the thresholds measured in BC modality in the experiment with respect to the estimated optimal integration calculated from the unimodal thresholds, considering the forearm and the palm, respectively. The lower the distance from the dashed bisector, the higher is the MLE integration, i.e. the closeness to the theoretical MLE integration. What is noticeable is that for low discrimination thresholds, experimental values are in agreement with MLE estimations. For higher thresholds, the experimental data diverges from the theoretical estimated thresholds.



(a) Forearm



(b) Palm

Fig. 5: JNDs of the psychometric functions for all modalities on the forearm (top) and on the palm (bottom). The JND was calculated from z-transformed time intervals. Colors: red indicates equal intervals (control condition), blue indicates the first interval long, and green indicates the first interval short.

C. Relation between Kappa effect and JND

Figure 7 reports the scatterplot of the magnitude of the Kappa effect as function of the JND of individual participants calculated separately for each modality on the forearm and the palm, respectively. A Spearman's analysis between the magnitude of the Kappa effect and mean JND revealed significant correlations for the stimulation on the palm in visual $R = .89, p < .0001$, tactile $R = 0.88, p < .0001$, BC $R = 0.94, p < .0001$, and BIV $R = 0.90, p < .0001$, whereas for the stimulation on the forearm there were significant correlations in visual $R = 0.78, p < .001$, tactile $R = 0.80, p < .001$, BC $R = 0.88, p < .0001$, BIV $R = 0.85, p < .0001$, and BIT $R = 0.54, p < .05$;

IV. Discussion

We demonstrated that perceptual illusions associated with the Kappa effect can be elicited with concurrent visual and tactile stimuli. Such perceptual illusions are associated with high inter-subject variability, especially in terms of the magnitude of the Kappa effect, which is defined as the difference between the PSE computed for the short (S) and long (L) spatial interval conditions. Building on previous evidence [2], [10], [11], our findings confirm the presence of the Kappa effect both in the visual and tactile domain, also at the same body site as suggested by previous research [6], [16]. Differently from [14], [15], we characterised the Kappa effect in touch considering, contiguous areas of the skin. Moreover, with respect to the study of Hidaka [16] our results are not dependent on the anisotropy properties of the skin. As shown in figures 3 and 4, there are no differences between the forearm and the hand in terms of the magnitude of the Kappa effect in the tactile domain. This finding can be ascribed to the distance between the tactile actuators of the wearable devices used in the experiments: this distance was increased from 14 mm, in

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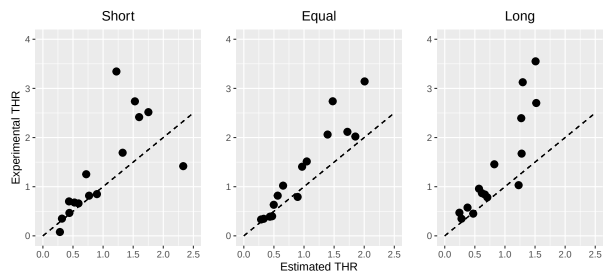
TABLE III: Differences in JND due to the factor Space in the Palm and Forearm for all Modalities(Friedman test)

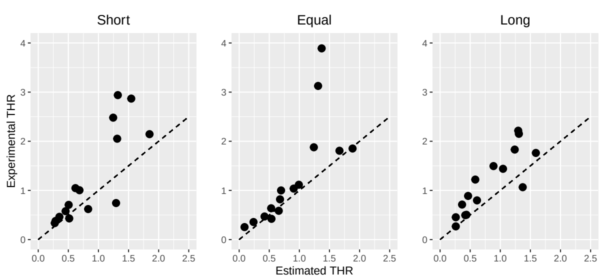
Place	**Visual**	**Tactile**	**BC**	**BIV**	**BIT**
Palm	Q=3.3 (p=0.18)	Q=2.1 (p=0.34)	Q=1.2 (p=0.54)	Q=0.6 (p=0.79)	Q=1.6 (p=0.19)
Forearm	Q=4.9 (p=0.08)	Q=0.9 (p=0.63)	Q=4.8 (p=0.08)	Q=1.7 (p=0.4)	Q=3.6 (p=0.16)

TABLE IV: Differences in JND due to the factor Modality in the Palm and Forearm for all Spaces (Friedman test)

Place	**Short**	**Equal**	**Long**
Palm	Q=4.0 (p=0.4)	Q=10.1 (p=0.006)	Q=1.6 (p=0.79)
Forearm	Q=9.7 (p=0.05)	Q=20.2 (p=0.0004)	Q=1.8 (p=0.76)



(a) Forearm



(b) Palm

Fig. 6: Discrimination thresholds (THR) in the BC modality vs. theoretical MLE thresholds calculated on the forearm data (top) and on the palm data (bottom). Optimal integration occurs for all the dots on the dashed lines.

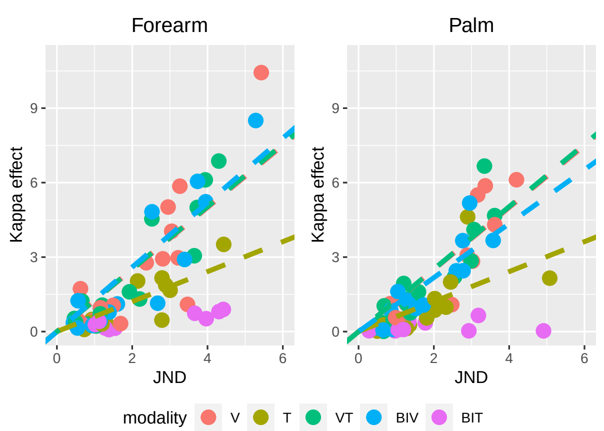


Fig. 7: Scatterplot of the magnitude of the Kappa effect as a function of mean JND of each participant on the forearm (left) and the palm (right). Both the parameters were calculated from z-transformed time intervals.

the wearable device for the palm, to 42 mm, in the wearable device for the forearm, according to the different two-point discrimination thresholds of the two body locations tested [32], [33].

Compared to previous studies, the stimulation protocol we developed envisioned the delivery of visual and tactile stimuli to the same body site, thus enabling a direct comparison of the modality-specific Kappa effect that was not possible to be performed within the data available from the existing literature. In each trial of the experiment, the comparison of the two inter stimulus intervals was affected by the perceptual channels involved (i.e., visual and/or tactile) concerning both spatial and temporal domains. In the unimodal conditions, the magnitude of the Kappa effect was generally greater in vision than in touch ($p < .05$), in agreement with the literature. The different magnitudes of the Kappa effect between vision and somatosensation are related to the higher spatial acuity (i.e. the lower sensory variance) of the visual channel (i.e. a greater ability to perceive differences in space) that is almost twice with respect to the tactile one in the body site we tested [20].

Building on previous literature [3], [19], we hypothesized that the Kappa effect across different perceptual modalities could rely on the cross-modal integration between sensory channels (vision and touch) within spatial and temporal domains, following the framework of MLE [40]. To this end, the lower discrimination thresholds of vision than touch in the spatial domain ($\sim 2.2\ mm$ vs. $\sim 4.7\ mm$ [20]) as opposed to the lower discrimination thresholds of touch with respect to vision in the time domain [38], [46] (i.e. $\sim 160\ ms$ vs. $\sim 197\ ms$). However, since the differences between the perceptual channels are much greater in the spatial domain, and considering that the Kappa effect arises from spatial information, the overall multisensory integration should preserve the illusory effect. The experimental results are in agreement with our hypothesis: in fact, in the control condition (i.e. equal spaces) we found a quasi-optimal integration in the time domain, meaning that visual and tactile stimuli were associated to a single event and that the temporal information was integrated within the MLE framework [19] (see Fig. 5a and 5b).

However, when the vision provided the illusory effect (i.e. the BC and the BIV condition), such an integration in the time domain did not affect the magnitude of the Kappa effect in multimodality. Conversely, in the BIT modality, the Kappa effect induced only by the tactile channel was disrupted by the equal spatial distances marked by the visual stimuli. The overall result in this modality was the absence of the Kappa

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effect (see Fig.4). These results are in agreement with the studies of Lyons *et al.* [24] and Craig [25] on the apparent motion, which reported that the lack of spatial congruence between the visual and the tactile stimuli direction resulted in perceptual illusions dominated by vision. Our results are in agreement also with the study of Asai et al. [21] concerning unified representations of the apparent motion by using multimodal concurrent stimulation when stimuli are congruent among each-other.

Interestingly, our results also show a linear dependency between the ability to discriminate time intervals (i.e. a value inversely proportional to the JND) and the magnitude of the Kappa effect experienced by the subject in the different modalities (see Fig. 7). To this end, we speculate that the measurement of the duration discrimination threshold of a specific subject can be used as a predictor of the magnitude of the Kappa effect in future applications. In particular, the possible modulation of the Kappa effect in virtual reality (VR) [29] can be profitably used in VRET allowing for the creation of a safe virtual world where patients can experience new realities relying on perceptual illusions [28]. As of today, the manipulation of patients' XR has largely ignored the temporal dimension, which could offer promising tools to identify new behavioural measures of patients' executive functioning, implicit decision-making patterns and memory, thus leading to the identification of clinically relevant, yet unknown subtypes (endophenotypes) of affective disorders. However, for VRET to be effective, it is mandatory to elicit in patients' a sense of immersion in XR. This can be guaranteed by capitalizing on multimodal stimulation, mainly relying on visual and tactile stimuli [47]. We speculate that the tactile stimuli we designed, associated to various visual events, like the collision of virtual objects bouncing on top of the participants' skin, should improve the sense of immersion in VR, while supporting the Kappa effect driven by the visual domain.

V. Conclusion

In this work we provided, for the first time, a comprehensive characterization of the Kappa effect in the visual-tactile conditions, within the peripersonal space (i.e., at the palm and the forearm), considering both unimodal and concurrent multimodal elicitations.

Although the origin of this perceptual space-time illusion is unknown, the application of Beyesian models to encode the Kappa effect showed that the representation of the internal time is a logarithmic function of physical time and physical distance that follows the Weber–Fechner law [7]. Therefore, this can be used to relate the integration strategies occurring across different sensory domains to the resulting magnitude of the Kappa effect.

To this regard, in future work we plan to evaluate the possible priors underpinning the Kappa effect, by further investigating a systematic space-time manipulation of virtual objects in both the visual and tactile domain in XR. In particular, the programmable elicitation of the Kappa Effect in XR could be used to design new experimental protocols for manipulating the perception of self in time. This could open also to the interesting scenarios of emotion modulation through the parametric tuning of time perception, thus unlocking a plethora of VR-based activities as well as a number of exploitation avenues in the diagnosis and re-stratification of affective disorders, with the possibility of devising novel therapeutic strategies.

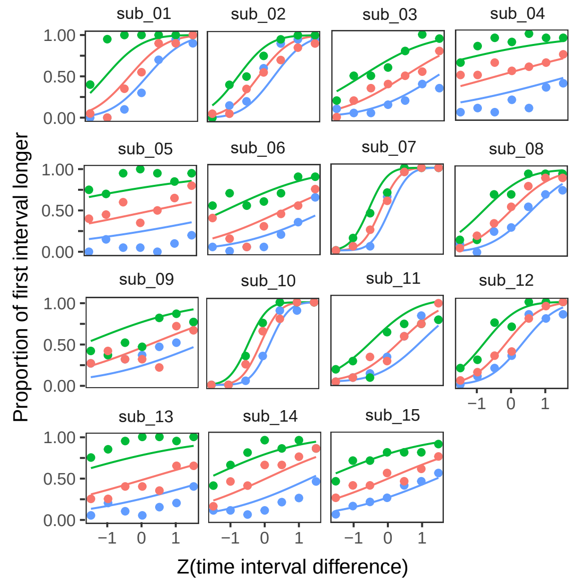

Fig. 8: GLMM of duration discrimination task in the visual unimodal modality (forearm). Colors: red indicates equal intervals (control condition), blue indicates the first interval long, and green indicates the first interval short.

Appendix: Generalized Linear Mixed Modeling

By means of multiple generalized linear mixed model (GLMM), we tested whether the factor space (short, equal, long) affected Kappa effect for each modality and place. GLMM indicates the effect of the experimental variables and for the variability between participants by means of fixed- and random- effect parameters, respectively [48]. Models were of the form:

$$\Phi^{-1}[P(Y=1)] = \beta_0 + u0 + \beta_1 \cdot x + u1 \cdot x + \beta_2(S) + \beta_3(L) \quad (2)$$

where Φ^{-1} is the probit link function, $P(Y = 1)$ is the probability of perceiving the first stimulus as longer than the second, β_* and u_* are the fixed- and random- effect parameters, respectively. S and L are two dummy variables correspondent to the levels of the factor Space short(S) and long(L).

Tables V and VI report the coefficients of the unimodal and multimodal models, respectively. In agreement with the previous data analysis, for all modalities and places the coefficient β_0, representing the PSE of control condition, reports values close to zero, therefore always not significant. The coefficient β_1, significant in all modalities and places, is related to the inverse of standard deviation of the psychometric function (i.e., JND = $0.75/\beta_1$). The coefficients β_2 and β_3 are related to the short and long condition, respectively: the PSE of the corresponding psychometric functions can be calculated as $-(\beta_0 + \beta_2)/\ \beta_1$ and $-(\beta_0 + \beta_3)/\beta_1$. The value of such coefficients, usually specular to zero, changes with modalities in agreement with Fig. 3. For instance, β_2 in the visual modality is twice the tactile modality. Regarding the factor Place, for all the modalities the coefficients are within the range of the SE. In general,the random effect in the models showed a limited variance $(0.04 - 0.08)$ on the intercept, whereas it showed a greater variance on the slope $(0.3 - 0.8)$, meaning that the discrimination thresholds were different among the participants.

We investigated also if the subject-specific effects were correlated with any of the static predictors. In particular, age and arm length values were standardized, and linear models were fitted between such predictors and both random intercepts and slopes. Whereas the coefficients were always not significant, the AIC parameter increased in all the configurations tested, meaning that such parameters were not improving the model fit. Figure 8 reports the GLMM of the unimodal visual modalitiy applied on the experimental data for each participants. Although the GLMM only provides 3 significant parameters for each factor combination of Modality and Place, it nevertheless allows us to represent the Magnitude of the Kappa effect (i.e., the translation of the PSE on the $x-$axis) and the JND of most of the participants. However, compared to the psychometric functions individually computed on the experimental data, the GLMM is unable to fit the data of specific participants which report an unbalanced Kappa effect (e.g., Fig.8 sub1 long, sub9 short, sub 11 short).

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TABLE V: Coefficients of fixed effects the unimodal models (with SE) Significance levels: *=0.01, **=0.001, ***=0.0001

Modality	**Visual**		**Tactile**	
Place	Palm	Forearm	Palm	Forearm
β_0	0.15 (0.07)	0.01 (0.07)	0.06 (0.06)	0.03 (0.06)
β_1	1.05 (0.18)***	0.92 (0.17)***	1.21 (0.21)***	1.08 (0.14)***
β_2	-0.59 (0.05)***	-0.61 (0.05)***	-0.28 (0.05)***	-0.34 (0.05)***
β_3	0.76 (0.05)***	0.82 (0.05)***	0.40 (0.05)***	0.33 (0.05)***

TABLE VI: **Coefficients of fixed effects the models (with SE)** Significance levels: *=0.01, **=0.001, ***=0.0001

Modality	**BC**		**BIV**		**BIT**	
Place	Palm	Forearm	Palm	Forearm	Palm	Forearm
β_0	0.08 (0.08)	0.00 (0.07)	0.07 (0.08)	-0.01 (0.06)	0.07 (0.08)	-0.01 (0.07)
β_1	1.27 (0.22)***	1.16 (0.20)***	1.24 (0.22)***	1.24 (0.23)***	1.22 (0.23)***	1.16 (0.21)***
β_2	-0.66 (0.05)***	-0.55 (0.05)***	-0.60 (0.05)***	-0.51 (0.05)***	-0.04 (0.05)	-0.12 (0.05)*
β_3	0.74 (0.05)***	0.83 (0.05)***	0.64 (0.05)***	0.80 (0.05)***	0.13 (0.05)**	0.11 (0.05)*

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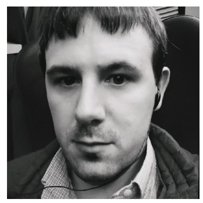

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