The Kappa Effect With Only Two Visual Markers

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Abstract

The *kappa effect* is a spatiotemporal illusion where duration is overestimated with the increase of space. This effect is typically demonstrated with three successive stimuli marking two neighboring empty time intervals, and the classical imputed velocity model, in principle, does not help to predict any spatial effects when only two stimuli, marking single intervals, are presented on each trial. We thus conducted three experiments, examining requirements for the occurrence of the kappa effect with only two visual stimuli. An interstimulus interval between the two stimuli was 217 (short) or 283 ms (long), and participants categorized the presented interval as ‘short’ or ‘long’. The key finding is that participants tended to respond ‘short’ more frequently than ‘long’ when both stimuli were delivered from the same location, whereas the relative frequency of ‘long’ responses was increased when the two stimuli were delivered from different locations in most directions (i.e., horizontally, vertically, diagonally; Experiment 1). This kappa effect clearly occurred when each stimulus was located 8° apart from the fovea in visual angle, but it was reduced when each stimulus was further deviated from the fovea, regardless of whether the two stimuli were presented in the vertical or the horizontal direction (Experiments 2 and 3). Moreover, increasing the spatial distance between the two stimuli from 15 to 30 cm magnified the effect only in a limited condition (Experiment 3). Implications of these results were discussed in terms of the Bayesian model predicting the effects of spatial acuity.

Keywords

Kappa effect, vision, interstimulus interval, discrimination, time–space dependency

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1. Introduction¹

The perceptual dependency of space and time has recently attracted attention from several neuroscience researchers (Bonato *et al.*, 2012; Buetti and Walsh, 2009; Martinez-Cascales *et al.*, 2013; Vallesi *et al.*, 2011), whereas this issue was already a scientific concern early in the 20th century for researchers in psychophysics (Abe, 1935; Helson, 1930). The *kappa effect* is one of the most famous illusions involving spatiotemporal interactions (Abe, 1935; Cohen *et al.*, 1953, 1955; see Jones and Huang, 1982 for a review). This effect takes place, for example, with three flashes, A, B and C, which are presented successively at equal temporal intervals. Two neighboring time intervals, A–B and B–C, are perceived as equivalent to each other if these flashes are aligned at equal spatial intervals. However, duration A–B is perceived as shorter than duration B–C, despite the physical equality of these durations, if B is spatially closer to A than to C; also, duration A–B is perceived as longer than duration B–C if B is spatially closer to C than to A. Thus, the effect is interpreted as indicating a perceptual tendency to overestimate duration when spatial distance is increased.

The kappa effect is explained by the imputed velocity model, positing the constancy of motional speed or velocity (Alards-Tomalin *et al.*, 2013; Henry and McAuley, 2009; Jones and Huang, 1982; Sarrazin *et al.*, 2004; ten Hoopen *et al.*, 2008). According to this model, the kappa effect (three stimuli) pattern is perceived as consisting of a single object appearing three times, instead of three discrete objects appearing successively. This single object is perceived as passing through space with constant speed. Speed constancy is physically kept when three stimuli are presented at equal temporal intervals and at equal spatial distances, but not if the middle stimulus is placed closer to the initial or to the last one while time intervals are kept equal. This speed inconstancy is readjusted by the perceptual system. Thus, the first time interval is perceived as shorter than the second one when the middle stimulus is closer to the initial one; also, the first time interval is perceived as longer than the second one when the middle stimulus is closer to the last one. The single object is consequently perceived as moving between three spatial locations with constant speed.

The imputed velocity model successfully explains the kappa effect when three stimuli are presented, whereas it does not help to predict any spatial effects on the perception of single time intervals delimited by two stimuli. Indeed, the presentation of only two stimuli does not imply whether speed is constant or not. Despite this theoretical limitation, Price-Williams (1954)

¹ Part of the current data was presented at the 22nd Virtual Reality Psychology International Conference held in Fukuoka in 2013.

found phenomena that seemed to be a variation of the kappa effect with single intervals. Participants were asked to reproduce the duration of empty intervals between two flashes by holding down a Morse key. In general, the reproduced duration was increased as the spatial distance between the two stimuli was increased. This result was explained by Jones and Huang (1982) on the basis of the imputed velocity model, although they did not explain why speed constancy could be inferred from the presentation of only two stimuli.

Another theoretical approach to the kappa effect was taken by Goldreich (2007). He did a modeling study that explained several tactile spatiotemporal effects, including the kappa effect, utilizing a Bayesian approach that seems applicable to the single interval presentation. This model posits the prior knowledge that two stimuli are perceived as a single object moving *slowly* between different spatial locations. In other words, slow movement is expected for a succession of two (or more) stimuli. Since the kappa effect sequences consist of a rapid succession of two stimuli, the Bayesian observer increases empty duration between the two stimuli so that the single object is perceived as moving slowly. The author did not explain why the motion must be perceived as slow (or what empirical data the assumption of the prior was based on), and this might be a limitation of the model. However, the Bayesian model and the imputed velocity model have a common assumption, namely that a motion is imputed by a succession of stimuli, suggesting the same mechanism underlying the kappa effect regardless of whether single intervals or two neighboring intervals are presented. However, only limited studies have tested the kappa effect with single intervals (for vision, Grondin, 1998; Newman and Lee, 1972; Price-Williams, 1954; for audition, Roy *et al.*, 2011; and for tactile stimuli, Grondin *et al.*, 2011; Kuroda and Grondin, 2013; Kuroda and Miyazaki, 2016). We therefore reopened the question whether the perception of single time intervals is influenced by spatial *distance* between two markers. This was the first issue of the present study.

A potential difference between horizontal and vertical presentations was also targeted in the present study. Guay and Grondin (2001) indicated that a longer spatial distance yielded a shorter perceived duration when each of the two successive flashes was delivered from one of the three locations aligned on a vertical axis; the above (A), the middle (M), and the below (B). Participants categorized the presented duration as ‘short’ or ‘long’. There were more ‘short’ responses when the empty duration was marked by A and B than when marked by A and M or by M and B. This appeared opposite to what was found in the study of Price-Williams (1954), where two stimuli were aligned on a horizontal axis. It is difficult, however, to compare these studies directly because they differed in technical procedures as well as the experimental settings. In the present series of experiments, we addressed the potential effect of

one factor differing between Guay and Grondin's and Price-Williams' experiments: presenting stimuli horizontally vs. vertically.

In summary, we conducted a series of psychophysical experiments in order to examine, firstly, if the kappa effect could be replicated with the presentation of only two visual stimuli, and secondly, if there would be a difference between horizontal and vertical presentations.

2. Experiment 1

Two successive stimuli were delivered from identical or different locations in the present experiment. When the two stimuli were delivered from different locations, they were aligned horizontally, vertically, or diagonally. Perceived duration in each spatial condition was tested with the categorization method, as used in Grondin (1998), where participants categorized the presented interval as 'short' (217 ms) or 'long' (283 ms).

2.1. Method

2.1.1. Participants

Fifteen participants (11 females) were recruited. They were students or employees at Kyushu University aged 20–32 years. They selfreported being righthanders and having normal noncorrected or corrected visual acuity. Written informed consent was obtained from each participant.

2.1.2. Apparatus and Stimuli

Participants were seated around 0.75 m in front of a Sony CRT monitor with a refresh rate of 60 Hz in a dimly lit room, around 6.5 lx. Each trial consisted of two successive white dots, around 73 cd/m², that were displayed on a black background. The diameter of each dot was 5 mm. There were four possible locations from which each dot was delivered (Fig. 1). Each location was 10.5 cm (8° in visual angle) apart from a point fixated by participants (i.e., fovea). The fixation point was a red cross with a size of 5 mm.

Each of the two dots was delivered from one of the four locations, resulting in 16 spatial conditions (= 4 first dot locations × 4 second dot locations). These conditions could be divided into four groups according to the direction in which the two dots were aligned: the *identical*, the *horizontal*, the *vertical*, and the *diagonal* conditions (Fig. 2). The interstimulus interval between the two dots was around 217 ms (= 13 frames ÷ 60 Hz × 1000; short interval) or 283 ms (= 17 frames ÷ 60 Hz × 1000; long interval). Each dot lasted around 50 ms (= 3 frames ÷ 60 Hz × 1000). Neurobehavioral Systems Presentation software was used to make a program running the experiment.

Note that there was a technical limitation in the vertical and the diagonal presentations. Because CRT displays refresh from the top to the bottom, upper

Figure 1. Spatial locations from which visual stimuli were delivered in Experiment 1 (left), Experiment 2 (middle) and Experiment 3 (right). Visual stimuli were white dots in Experiment 1 and white LEDs in Experiments 2 and 3. The fixation point was a red cross in Experiment 1 and a red LED in Experiments 2 and 3.

objects are displayed physically faster, and thus an empty time interval between two stimuli is physically shorter when these stimuli are presented in the upward direction than when presented in the downward direction. In order to cancel out any effects resulting from this physical difference, we averaged the results of the upward and downward directions in the data analysis (Fig. 2).

2.1.3. Procedure

The categorization method as used in Grondin (1998) was adopted. Participants were informed that each trial consisted of two successive dots and that the interstimulus interval between these dots was shorter or longer than 250 ms. Participants responded whether the interval was ‘short’ (for 217 ms) or ‘long’ (283 ms). After the response, a feedback message indicating whether the response was correct or incorrect with the correct answer (for example, ‘Correct: Short’) was displayed at the center of the display during 1.2 s. The next trial started 1 s after the termination of the feedback. Feedback was presented throughout the experiment.

Two sessions were completed in one day (about 35 min per session). Eight participants first conducted a session where ‘short’ and ‘long’ were assigned to the left and the right mouse button, respectively, and then a session where the role of the two buttons was interchanged. The other participants conducted these sessions in the opposite order. Collapsing these sessions eliminated a potential response bias that could be found in temporal discrimination (e.g., STEARC effect; see Ishihara *et al.*, 2008; Mioni *et al.*, 2014; Vallesi *et al.*, 2011) (see Note 1). Each session was divided into eight blocks. In each block, the 32 sequences (= 16 locations × 2 intervals) were presented twice, each

Figure 2. Spatial conditions in Experiment 1. These conditions were grouped according to a 2 (initial position) × 4 (direction) design.

in a random order, resulting in 64 trials. A break of a few seconds was taken between the blocks.

Participants were instructed to respond as correctly as possible, but for the first few trials of the first block, they were allowed to choose ‘short’ or ‘long’ randomly because they did not know how long the 250 ms interval would be perceived as. Indeed, the first block of each session was regarded as training and removed from the data analysis. Participants were instructed not to adjust their perceived duration according to spatial distance between presented stimuli. They were also instructed not to count the cadence or make sounds

synchronized with dots (e.g., hand tapping and internal voicing) for discrimination. Hand tapping and internal voicing might reduce the spatial effects because sounds were made at a constant location.

2.1.4. Data Analyses

As mentioned earlier, the first block of each session was regarded as training and removed from the data analysis. Since the two sessions were collapsed, each of the dependent variables that are explained below was based on 28 responses ($= 2 \text{ sessions} \times 7 \text{ blocks} \times 2 \text{ responses}$). Then, the results of the upward and of the downward direction were averaged for the vertical and diagonal conditions due to the technical problem mentioned earlier; also, for the identical and the horizontal conditions, the results when the two dots were located on the upper side and those when the two dots were on the bottom side were averaged. Thus, the current analysis was based on a $2 \text{ (initial-marker position)} \times 4 \text{ (direction)}$ design (Fig. 2).

A signal detection theory measure, β , was estimated from participants' responses (Macmillan and Creelman, 2005; Stanislaw and Todorov, 1999). As in Grondin (1998), this variable was used to examine how likely participants were to perceive intervals as 'long' instead of 'short'; a lower value indicates that participants were likely to respond 'long'. Note that β is usually used in detection tasks to express the tendency for participants to prefer responding to one of the two alternatives, while in the present study this measure is interpreted as a sign of perceived duration; if intervals are perceived as longer, participants should respond 'long' more frequently than 'short', resulting in lower β (see also Kuroda and Grondin, 2013). In the Appendix, we also estimate another measure, d' , expressing how well participants discriminated between the 217 ms and the 283 ms intervals (i.e., temporal sensitivity).

β was calculated by the following equation:

$$\beta = \exp \left\{ \frac{[\Phi^{-1}(F)]^2 - [\Phi^{-1}(H)]^2}{2} \right\}, \quad (1)$$

$\Phi^{-1}(H)$ is a z score of the hit probability and $\Phi^{-1}(F)$ is a z score of the false alarm probability. The hit probability here means how frequently participants correctly responded 'long' when the interval was actually long (i.e., 283 ms). The false alarm probability means how frequently participants wrongly responded 'long' when the interval was actually short (i.e., 217 ms). The log-linear method was adopted for correcting each probability in order to avoid obtaining extreme values (0 and 1) which led to infinity when converted into the z score (Hautus, 1995; Macmillan and Creelman, 2005). We indeed used $\log_{10} \beta$ instead of β for keeping the linearity of scale, as in Grondin (1998). A $\log_{10} \beta$ of zero indicates that the number of 'short' responses was equal to that of 'long' responses. $\log_{10} \beta$ above zero indicates that participants tended

to respond ‘short’ while $\log_{10} \beta$ below zero indicates that participants tended to respond ‘long’.

An analysis of variance (ANOVA) based on the linear mixed effect model (LMEM) was conducted on $\log_{10} \beta$ using the ‘lmerTest’ package in R software. In this model, the fixed effects were the initial marker position and the direction, while the random effect was the participants. Degrees of freedom were estimated with the Satterthwaite method. When the interaction was significant, the simple main effects of the initial position and of the direction were tested each with one-way LMEM ANOVA. When the main or simple effects of the direction were significant, pairwise comparisons were conducted according to the Holm method that corrected the p value corresponding to the difference of least square means estimated in LMEM.

2.2. Results and Discussion

Boxplots of $\log_{10} \beta$ are shown in Fig. 3. An LMEM ANOVA (Note 2) showed that the direction effect, $F(3, 42) = 19.577$, $p < 0.001$, as well as the interaction, $F(3, 42) = 4.552$, $p = 0.008$, was significant, while the initial-position effect was not significant, $F(1, 14) = 0.489$, $p = 0.496$. The results of the *post hoc* analysis are reported in Fig. 3. In brief, the kappa effect occurred when only two stimuli were used in most of the directions tested. Indeed, empty duration was perceived as longer, i.e., $\log_{10} \beta$ was lower, when two visual markers were delivered from different locations (in the horizontal, vertical and diagonal conditions) than when both were delivered from identical locations. Unexpectedly, the $\log_{10} \beta$ was lower when both markers were delivered from the left side (left side identical condition) than when delivered from the right

Figure 3. Boxplots of $\log_{10} \beta$ for each experimental condition of Experiment 1. Each box consists of a minimum, a lower quartile, a median, an upper quartile, and a maximum value. ‘x’ represents a mean. Significant differences revealed by the *post hoc* analysis are also shown (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

side (right side identical condition; for twelve of fifteen participants). In addition, no significant difference was found between the identical and horizontal conditions when the initial dot was delivered from the left side. We will find whether these results could be replicated in Experiment 3.

3. Experiment 2

The result that the kappa effect occurred in the vertical direction in Experiment 1 seemed inconsistent with that reported by Guay and Grondin (2001) where longer distance yielded shorter perceived duration when two flashes were aligned vertically. This inconsistency might be due to the technical procedures adopted in these experiments. Guay and Grondin compared the short (A–M and M–B) and long (A–B) distances, whereas in Experiment 1 we compared the condition where no space was given between two stimuli (in the identical condition) and the one where a space was given between them (in the horizontal, vertical and diagonal conditions). We thus added the short vs. long distance comparisons in the present experiment, using only the vertical direction. Furthermore, the technical problem involving the vertical presentations in Experiment 1 was solved with TTL signals actuating light emitting diodes (LEDs; see below for details).

The present experiment was also designed to test the validity of the predication that was given by Goldreich (2007) on the basis of the Bayesian model. One version of this model (called the full Bayesian observer model) consisted of three parameters. The first parameter was the degree of expectation for slow movement (σ_v), the second was temporal acuity (σ_t), and the last was spatial acuity (σ_s). The equation (equation (16); see also Fig. 6D in that article) showed that the kappa effect is reduced when each marker is presented at a tactile location of poor spatial acuity (higher σ_s). Although the model was constructed for tactile phenomena, Goldreich predicted, from this result, “a greater kappa effect for foveal than peripheral stimulus sequences” (p. 8) in the visual modality. Seemingly, this prediction is in contradiction with the notion that empty duration is perceived as longer when spatial distance is longer, as indicated by Price-Williams (1954). If a visual stimulus is located on one lateral side and another stimulus on the opposite side, the spatial distance between these stimuli is physically longer when the two stimuli are located on the peripheral side than when located on the central side. However, according to Goldreich’s prediction, the kappa effect is rather reduced if the two stimuli are located peripherally because of a poor spatial acuity of the field. Indeed, an underestimation effect, instead of the kappa effect, occurred in Guay and Grondin (2001) where each marker was located farther away (14° apart in visual angle) from the fovea.

We found in Experiment 1 that the kappa effect occurred when each marker was located 8° apart from the fovea. This condition was adopted and called the near fovea (short distance) condition in the present experiment. We also prepared the far from fovea (long distance) condition where each marker was located farther away from the fovea so that the spatial distance between the upper and bottom locations was doubled (30 cm) compared with the near fovea condition (15 cm; see Fig. 1b). We examined whether the kappa effect would be magnified or reduced in the far from fovea (long distance) condition, compared with the near fovea (short distance) condition.

3.1. Method

3.1.1. Participants

Twelve participants (6 females) were recruited. They were students at Shizuoka University aged 19–22 years. They self-reported being righthanders and having normal noncorrected or corrected visual acuity. Written informed consent was obtained from each participant.

3.1.2. Apparatus and Stimuli

Participants were seated around 0.75 m in front of a black cardboard panel on which eight white LEDs (Cree C503C-WAN) were located, as shown in Fig. 1b, in a dimly lit room around 6.5 lx. The diameter of each LED was 5 mm. The four LEDs (2, 3, 6 and 7 in Fig. 1b) that were each located 8° apart from the fixation point corresponded to the four dots used in Experiment 1. Of these four LEDs, the higher ones (2, 6) were separated from the lower ones (3, 7) by 15 cm on a vertical axis. Each of the other LEDs (1, 4, 5, 8) was located around 13° apart from the fovea, and the highest ones (1, 5) were separated from the lowest ones (4, 8) by 30 cm. The fixation point was a red LED (Cree C503C-RAN).

Each LED was lit or unlit by TTL signals outputted from the parallel port of the computer. The timing of TTL signals was controlled by Neurobehavioral Systems Presentation software. We checked that the physical timing of flashes was reasonably correct with photo sensors. The luminance of these LEDs was calibrated between 74 and 80 cd/m^2 . Potentiometers (variable resistances) were used for the calibration, but it was technically difficult to fix all LEDs at exactly the same luminance. In order to reduce potential effects of luminance differences among the eight LEDs, we interchanged the locations of these LEDs by flipping the panel by 180° for half the participants.

Sixteen experimental conditions are summarized in Table 1 and these were grouped according to a 2 (distance) $\times$ 2 (hemifield) $\times$ 4 (direction) design. More specifically, two flashes were delivered from the same LED or from different LEDs on either the left or the right hemifield. The long distance (far from fovea) sequences consisted of the highest (1, 5) and the lowest LEDs

Table 1.

LEDs lit in each experimental condition of Experiments 2 and 3

Direction of two flashes	LEDs far from fovea (involving long distance)		LEDs near fovea (involving short distance)	
	Left side	Right side	Left side	Right side
Experiment 2				
Identical (upper–upper)	1–1	5–5	2–2	6–6
Identical (bottom–bottom)	4–4	8–8	3–3	7–7
Downward (upper–bottom)	1–4	5–8	2–3	6–7
Upward (bottom–upper)	4–1	8–5	3–2	7–6
Experiment 3	Upper side	Bottom side	Upper side	Bottom side
Identical (left–left)	1–1	5–5	2–2	6–6
Identical (right–right)	4–4	8–8	3–3	7–7
Rightward (left–right)	1–4	5–8	2–3	6–7
Leftward (right–left)	4–1	8–5	3–2	7–6

Note. The numbers in the table correspond to those indicated in Fig. 1, and represent the first–second LEDs that were lit in each trial.

(4, 8), while the short distance (near fovea) sequences consisted of the second highest (2, 6) and the second lowest LEDs (3, 7). In each sequence, the two flashes were presented in four directions: the upper identical (upper–upper), bottom identical (bottom–bottom), downward (upper–bottom) and upward (bottom–upper) condition. The interstimulus interval was 217 or 283 ms. Consequently, there were 32 sequences (16 locations $\times$ 2 durations).

3.1.3. Procedure and Data Analysis

The same procedure and data analysis as in Experiment 1 were adopted, except that the feedback messages were replaced with 300 ms sinusoidal sounds. A high pitch (2000 Hz) sound indicated that the response was correct while a low pitch (500 Hz) sound indicated that the response was incorrect. Since the present experiment had as many (32) sequences as Experiment 1, each of the two sessions were divided into eight blocks (including one practice), each one consisting of 64 trials (= 32 sequences $\times$ 2 responses), as in Experiment 1. Thus, each dependent variable was based on 28 responses (= 2 sessions $\times$ 7 blocks $\times$ 2 responses). The statistical analysis was based on a 2 (distance) $\times$ 2 (hemifield) $\times$ 4 (direction) design. These independent variables were the fixed effects and the participants were the random effect in LMEM.

3.2. Results and Discussion

The boxplots of $\log_{10} \beta$ are shown in Fig. 4. An LMEM ANOVA revealed that the direction effect, $F(3, 37.053) = 10.955$, $p < 0.001$, as well as its interaction with the distance, $F(3, 109.646) = 2.759$, $p = 0.046$, was significant.

Figure 4. Boxplots of $\log_{10} \beta$ (upper) and of the spatial effect index (lower), expressed by $0.5\{(\log_{10} \beta_{UB} + \log_{10} \beta_{BU}) - (\log_{10} \beta_{UU} + \log_{10} \beta_{BB})\}$, for each experimental condition of Experiment 2 where the vertical-presentation effects were tested. Significant differences revealed by the *post hoc* analysis are also shown. The left and right conditions were combined in the *post hoc* analysis for $\log_{10} \beta$ because the interactions involved with this factor were not significant. See Fig. 3 for the definition of the symbols.

None of the other effects was significant ($p > 0.104$) (Note 3). The results of the *post hoc* analysis are reported in Fig. 4.

The $\log_{10} \beta$ was significantly decreased, i.e., empty duration was overestimated, when the two flashes were delivered from different locations (upper–bottom and bottom–upper) compared with when delivered from identical locations (upper–upper and bottom–bottom), but only in the visual field near to the fovea (short distance conditions). When the two flashes were located farther

away from the fovea (in the long distance conditions), a significant difference was found in only two pairs of the direction conditions (bottom–bottom *vs.* upper–bottom and upper–upper *vs.* upper–bottom). Moreover, neither the upper–bottom nor bottom–upper sequences led to a significant difference between the near fovea and far from fovea conditions, indicating that the kappa effect was not magnified by increasing the spatial separation between the two flashes. In order to make a more quantitative comparison between the near and far from fovea conditions, the spatial effect index was estimated by subtracting the results of the identical location conditions (upper–upper and bottom–bottom) from those of the different location conditions (upper–bottom and bottom–upper), i.e., $0.5\{(\log_{10} \beta_{UB} + \log_{10} \beta_{BU}) - (\log_{10} \beta_{UU} + \log_{10} \beta_{BB})\}$. The results are shown in Fig. 4. An LMEM ANOVA, where the fixed effect was the field and the random effect was the participants, revealed that the near fovea condition led to a lower index (i.e., greater kappa effect) than the far from fovea condition, $F(1, 11) = 8.943$, $p = 0.012$. This finding is consistent with Goldreich's (2007) prediction of a greater kappa effect for foveal than peripheral sequences. Notably, Guay and Grondin (2001) reported that longer distance resulted in shorter perceived duration, and they placed the highest and lowest LEDs each 14° apart from the fovea. The kappa effect might be difficult to occur in the visual field that those authors used.

4. Experiment 3

The near fovea *vs.* far from fovea difference was also tested in the present experiment where the two flashes were aligned horizontally. Price-Williams (1954) presented two flashes in the horizontal direction but used empty intervals of 7 s or more, which were much longer than the ones used in the present study. Only a few studies tested the kappa effect with subsecond intervals marked by only two visual stimuli (e.g., Grondin, 1998). We thus examined in the present experiment whether the kappa effect would occur when the two flashes were presented horizontally in each visual (near fovea *vs.* far from fovea) field.

4.1. Method

4.1.1. Participants

Twelve participants (3 females) were recruited. They were students at Shizuoka University aged 20–23 years. They selfreported being righthanders and having normal noncorrected or corrected visual acuity. Six of them also took part in Experiment 2. Written informed consent was obtained from each participant.

4.1.2. Apparatus, Stimuli, Procedure, and Data Analysis

The same apparatus, stimuli, procedure, and data analysis as in Experiment 2 were adopted, except that two flashes were aligned horizontally. Indeed, the panel that was used in Experiment 2 was just flipped by 90° in the present experiment (Fig. 1c) and flipped by more 180° for half the participants in order to reduce potential effects of slight luminance differences among the LEDs. As shown in Table 1, the statistical analysis was based on a 2 (distance) $\times$ 2 (side) $\times$ 4 (direction) design.

4.2. Results and Discussion

The boxplots of $\log_{10} \beta$ are shown in Fig. 5. An LMEM ANOVA revealed that the distance effect, $F(1, 121) = 28.857$, $p < 0.001$, the direction effect, $F(3, 33) = 12.932$, $p < 0.001$, and the interaction between these two effects, $F(3, 121) = 4.766$, $p = 0.004$, were significant. None of the other effects was significant ($p > 0.551$) (Note 4). The results of the *post hoc* analysis are reported in Fig. 5.

When each flash was located far from the fovea (in the long distance conditions), the different location sequences (left–right, right–left) led to a significantly lower $\log_{10} \beta$ than the identical location sequences (left–left, right–right), except in a right–right vs. right–left comparison. However, when each flash was located closer to (8° apart from) the fovea, a significant difference was found in all pairs of the different vs. identical location sequences, indicating that the kappa effect occurred easier when each visual marker was located closer to the fovea. Indeed, when the spatial effect index was estimated with $0.5\{(\log_{10} \beta_{LR} + \log_{10} \beta_{RL}) - (\log_{10} \beta_{LL} + \log_{10} \beta_{RR})\}$ to compare the near fovea and far from fovea fields, an LMEM ANOVA showed that the near fovea condition resulted in a significantly lower index (i.e., stronger kappa effect) than the far from fovea condition, $F(1, 11) = 7.853$, $p = 0.017$ (Fig. 5). Note however that three of the four sequences (left–left, right–right, left–right) led to a significant $\log_{10} \beta$ difference between the long distance (far from fovea) and short distance (near fovea) conditions. We will discuss this result in the following section.

We reported in Experiment 1 that $\log_{10} \beta$ was significantly lower when both stimuli were delivered from the left hemifield (left–left) than when delivered from the right hemifield (right–right). This might result in a lack of difference between the identical and horizontal conditions when the first marker was delivered from the left hemifield (i.e., left–left vs. left–right) in Experiment 1. However, these results were not replicated in the present experiment where the physical parameters such as luminance and duration were more systematically controlled. It thus would be reasonable to conclude that the kappa effect takes place when two visual stimuli are aligned horizontally, but only if they are located not too far from the fovea.

Figure 5. Boxplots of $\log_{10} \beta$ (upper) and of the spatial effect index (lower), expressed by $0.5[(\log_{10} \beta_{LR} + \log_{10} \beta_{RL}) - (\log_{10} \beta_{LL} + \log_{10} \beta_{RR})]$, for each experimental condition of Experiment 3 where the horizontal presentation effects were tested. Significant differences revealed by the *post hoc* analysis are also shown. The upper and bottom conditions were combined in the *post hoc* analysis for $\log_{10} \beta$ because the interactions involved with this factor were not significant. See Fig. 3 for the definition of the symbols.

5. General Discussion

The present study was conducted in order to examine requirements for the occurrence of the kappa effect when only two visual stimuli are presented on each trial. A potential difference between the horizontal and vertical presentations was also targeted. The main results of the three experiments can be summarized as follows: In Experiment 1, participants tended to respond ‘short’ more frequently than ‘long’ when both stimuli were delivered from

the same location, whereas the relative frequency of ‘long’ responses was increased when the two stimuli were delivered from different locations in most directions (i.e., horizontally, vertically, diagonally). In Experiments 2 and 3, this kappa effect clearly occurred when each stimulus was located 8° apart from the fovea (i.e., in the near fovea conditions), but it was reduced when each stimulus was located 13° apart from the fovea (in the far from fovea conditions), regardless of whether the two stimuli were presented in the vertical or the horizontal direction. Moreover, increasing the spatial distance between the two stimuli from 15 to 30 cm boosted perceived duration only when the two stimuli were presented in the rightward directions (i.e., in the left–right sequences of Experiment 3).

It should be noted that feedback was presented on every trial of the present experiments and this continuous learning might have reduced the magnitude of the kappa effect. Nevertheless, the present results indicated the spatial conditions where the kappa effect occurs robustly with only two visual stimuli, resisting the learning effect. Indeed, the kappa effect occurs if these stimuli are located near the fovea. It seems difficult to explain this finding with the imputed velocity model positing speed constancy because the presentation of only two stimuli does not provide any change of speed. The finding can alternatively be explained with the Bayesian model (Goldreich, 2007) that posits the expectation of slow motion between stimulus locations. Goldreich predicted from this model that the kappa effect would be reduced when each stimulus is presented at a location of poor spatial acuity (higher σ_s). According to the model, the reduction of the kappa effect is attributed to the contraction of spatial distance between two tactile stimuli when the spatial acuity is poor. The expectation of slow motion is fulfilled by the elongation of perceived duration and/or the contraction of perceived distance, but the distance contraction is enhanced when the spatial acuity is poor, resulting in no need to elongate duration for producing slow motion. Notably, Cohen *et al.* (1953), using two neighboring intervals, also suggested that “Experiments in progress show that when the distance ratio [between the two intervals] is held constant the *kappa* effect increases with decrease in the visual angle [subtending the whole sequence]” (p. 901). However, the imputed velocity model and the Bayesian model are not mutually exclusive because these share the assumption that a motion is imputed by the succession of stimuli. The assumption of speed constancy in the imputed velocity model may be integrated into the Bayesian model when more than two stimuli are presented on each trial.

Grondin *et al.* (2011) reported a tactile version of the kappa effect with single intervals (see also Kuroda and Miyazaki, 2016; Suto, 1952). In their experiment, empty duration was perceived as longer when two electric pulses were presented on different hands than when both were presented on the same

hand. Kuroda and Grondin (2013) suggested, however, that this effect might partly be attributed to the latency of integrating two pulses that stimulate different cortical hemispheres when these pulses are presented on different hands. This observation by Kuroda and Grondin is inconsistent with the results of the present study; the kappa effect occurred when two markers were presented on a vertical line (Experiments 1 and 3), both markers stimulating a visual area of the same cortical hemisphere. We thus found no reason to posit the latency of interhemispheric transmissions in the kappa effect, at least, in the visual modality.

There was no clear evidence indicating a difference between the horizontal and vertical presentations in the present study. Indeed, the kappa effect occurred at least in the near fovea conditions in both Experiments 2 (vertical) and 3 (horizontal). If anything, the far from fovea (long distance) conditions resulted in longer perceived duration (lower $\log_{10} \beta$) than the near fovea (short distance) conditions when the two stimuli were presented in the rightward direction (the left–right sequences) of Experiment 3. This might be slight evidence indicating that the increase of the spatial distance from 15 to 30 cm magnified the kappa effect, and also that the kappa effect occurred easier in the horizontal than in the vertical presentations. However, no difference was found between these distance conditions for the leftward (right–left) sequences. The effects of increasing spatial distance might be fragile because they interact with the effects of spatial acuity as mentioned earlier. Note however that one limitation in the current discussion is based on the fact that the visibility of stimuli was not perfectly controlled in the experiments. The visibility might have been reduced for a flash farther away from the fovea, and this might have influenced perceived duration. Indeed, there was a significant difference between the far from fovea (long distance) and near fovea (short distance) conditions when both flashes were delivered from the same location (in the left–left and right–right sequences) in Experiment 3. Moreover, as indicated in the Appendix, sensitivity (d') was impaired when each marker was located far from the fovea for all of the directions. Thus, we must refrain giving much theoretical interpretations to the $\log_{10} \beta$ differences between the long distance and short distance conditions for each of the four sequences in Experiments 2 and 3. However, the comparisons among the four sequences *within* each distance condition are reasonably working because each flash was deviated from the fovea by the same visual angle within each distance condition, resulting in almost identical visibility. We, therefore, could keep the proposition that empty duration was overestimated, i.e., $\log_{10} \beta$ was decreased, when the two flashes were delivered from different locations, compared with when both were delivered from the same location, especially in the near fovea conditions.

Another limitation of the present study is that a point of subjective equality (in ms) could not be estimated from the data in the categorization method. This parameter is necessary for a quantitative assessment of the validity of the equation in the Bayesian model. A two-interval-forced-choice task (i.e., comparing the standard and comparison intervals) may be used for estimating the parameter. It should also be a future avenue to manipulate the point fixated by participants (as in Roussel *et al.*, 2009), which may be one of the methods to manipulate spatial acuity with keeping the physical location of stimuli.

In brief, the kappa effect occurs with only two visual markers if these markers are located not too far from the fovea, and this may reasonably be explained on the basis of the Bayesian model predicting the effects of spatial acuity. Given that Goldreich (2007) applied the Bayesian model to several spatiotemporal illusions including the kappa effect, a further investigation of the kappa effect may give new insights into understanding a neural principle that also underlies other spatiotemporal phenomena (Bonato *et al.*, 2012; Buetti and Walsh, 2009; Rocchesso *et al.*, 2013).

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Notes

1. When the two sessions were not collapsed and thus the experiment was based on a 2 (response-button combination) $\times$ 2 (initial-marker position) $\times$ 4 (direction) design, an analysis of variance (ANOVA) according to the linear mixed effect model revealed that the main effect and interactions involved with the response-button combination were not significant for both $\log_{10} \beta$ ($p > 0.069$) and d' ($p > 0.409$). Almost the same results were given by a classic repeated-measures ANOVA (for $\log_{10} \beta$, $p > 0.183$; for d' , $p > 0.353$).
2. We also checked that almost the same results were given by a classic repeated measures ANOVA according to a 2 (initial marker position) $\times$ 4 (direction) design. F distribution was estimated with degrees of freedom

that were adjusted with Greenhouse–Geisser epsilon against potential violation of sphericity. The direction effect, $F(1.69, 23.66) = 19.577$, $p < 0.001$, $\eta_p^2 = 0.583$, as well as the interaction, $F(2.06, 28.81) = 4.552$, $p = 0.018$, $\eta_p^2 = 0.245$, was significant, while the initial position effect was not significant, $F(1, 14) = 0.489$, $p = 0.496$, $\eta_p^2 = 0.034$.

3. Almost the same results were given by a classic three-way repeated measures ANOVA; the direction effect, $F(1.78, 19.56) = 10.667$, $p = 0.001$, $\eta_p^2 = 0.492$, as well as its interaction with the distance, $F(2.1, 23.12) = 4.092$, $p = 0.029$, $\eta_p^2 = 0.271$, was significant. None of the other effects was significant ($p > 0.266$). In addition, a one-way repeated measures ANOVA revealed that the spatial effect index was lower in the near fovea than the far from fovea condition, $F(1, 11) = 8.943$, $p = 0.012$, $\eta_p^2 = 0.448$.
4. Almost the same results were given by a classic three-way repeated measures ANOVA; the distance effect, $F(1, 11) = 29.189$, $p < 0.001$, $\eta_p^2 = 0.726$, the direction effect, $F(1.47, 16.17) = 12.932$, $p = 0.001$, $\eta_p^2 = 0.540$, and the interaction between these two effects, $F(2.42, 26.66) = 4.116$, $p = 0.022$, $\eta_p^2 = 0.272$, were significant. None of the other effects was significant ($p > 0.551$). In addition, a one-way repeated measures ANOVA revealed that the spatial effect index was lower in the near fovea than the far from fovea condition, $F(1, 11) = 7.853$, $p = 0.017$, $\eta_p^2 = 0.417$.

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Appendix. Temporal Sensitivity

We also estimated d' in order to examine how well participants discriminate between the 217 ms and the 283 ms intervals (i.e., temporal sensitivity). d' was calculated with following equation:

$$d' = \Phi^{-1}(H) - \Phi^{-1}(F) \quad (2)$$

The results of Experiment 1 are shown in Fig. A1. An LMEM ANOVA revealed that the direction effect was significant, $F(3, 42) = 13.875$, $p < 0.001$, while neither the initial position effect, $F(1, 56) = 0.761$, $p = 0.387$, nor the interaction, $F(3, 56) = 1.193$, $p = 0.321$, was significant. The results of the *post hoc* analysis are reported in Fig. A1. In brief, presenting two markers at different locations resulted in impaired sensitivity (lower d') compared to presenting them at identical locations.

The results of Experiment 2 testing the vertical presentation effects are shown in Fig. A2. An LMEM ANOVA revealed that the distance effect, $F(1, 11) = 9.948$, $p = 0.009$, as well as the direction effect, $F(3, 33) = 4.231$, $p = 0.012$, was significant. None of the other effects was significant ($p > 0.056$). As presented in Fig. A2, the upper–upper sequences resulted in a significantly higher d' than the upper–bottom and bottom–upper

Figure A1. Boxplots of d' for each experimental condition of Experiment 1. Significant differences revealed by the *post hoc* analysis are also shown. The left and right conditions were combined in the *post hoc* analysis because the interaction was not significant. See Fig. 3 for the definition of the symbols.

Figure A2. Boxplots of d' for each experimental condition of Experiment 2 testing the vertical-presentation effects. Significant differences revealed by the *post hoc* analysis are also shown. The side (left and right) conditions and the field (near fovea and far from fovea) conditions were collapsed in the *post hoc* analysis because no interactions were significant. See Fig. 3 for the definition of the symbols.

sequences. This applied to both the near fovea (short distance) and the far from fovea (long distance) condition (no interaction between the distance and the direction). However, the main effect of distance was significant, indicating that sensitivity was impaired when each flash was located farther away from the fovea for all of the directions (this result is not reported in Fig. A2).

The results of Experiment 3 testing the horizontal-presentation effects are shown in Fig. A3. Almost the same results as in Experiment 2 were found. An LMEM ANOVA revealed that the distance effect, $F(1, 132) = 18.828$, $p < 0.001$, as well as the direction effect, $F(3, 33) = 7.364$, $p < 0.001$, was significant. None of the other effects was significant ($p > 0.409$). As presented in Fig. A3, the mean d' was decreased when two flashes were delivered from different locations compared with when delivered from identical locations, except in a comparison between the right–right and left–right sequences. This applied to both the long distance (far from fovea) and the short distance (near fovea) conditions (no interaction between the distance and the direction). However, the main effect of distance was significant, indicating that sensitivity was impaired when each flash was located farther away from the fovea for all of the directions.

Figure A3. Boxplots of d' for each experimental condition of Experiment 3 testing the horizontal-presentation effects. Significant differences revealed by the *post hoc* analysis are also shown. The side (upper and bottom) conditions and the field (near fovea and far from fovea) conditions were collapsed in the *post hoc* analysis because no interactions were significant. See Fig. 3 for the definition of the symbols.