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Interdependence between temporal and ambient spatial variations of a successive sound sequence

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ABSTRACT

Time and space are interdependent in perception. The most typical example is that the temporal and spatial patterns of three successive stimuli, defining two inter-onset intervals and two spatial distances, can respectively affect the experience of spatial and temporal variations. In regard to auditory modality, most studies have equated pitch space with ambient space and demonstrated that each of the temporal and pitch intervals can affect the respective perceptual pitch and temporal variations. A very interesting question is whether the interdependence between temporal and ambient spatial variations, not pitch variations, could be found when successive sounds differ in location. To investigate what effect temporal variations in a successive sound sequence had on the experience of spatial variations, we measured the subjective differences between two neighboring distances (Experiment 1) and subjective absolute locations (Experiment 2) when three successive sounds, S_1, S_2, and S_3, were presented to participants from different loudspeakers. The results demonstrated that varying the time interval between S_1 and S_2 (t_1) and between S_2 and S_3 (t_2) affected the perceived spatial distances between the sounds. If t_1 was larger than t_2, the subjective distance between S_1 and S_2 (d_1) was greater than that between S_2 and S_3 (d_2), although the physical distances of d_1 and d_2 were identical. The results indicate that there is a typical Tau effect in auditory modality, and the auditory Tau effect is caused by the mislocalization of S_2. Furthermore, the findings suggest that a perceptual, not physical, temporal pattern affects the experience of the auditory spatial layout. Spatial information on successive sounds may be organized after a sound sequence is temporally structured.

INTRODUCTION

Time and space are interdependent in perception. Temporal and spatial variations in a stimulus sequence can respectively affect the experience of the spatial and temporal layout in the visual and tactile modality. The most typical example is where each temporal variation or spatial variation of three successive stimuli, defining two temporal inter-onset intervals (IOIs) and two spatial distances, can affect the experience of each spatial variation or temporal variation. When two constant spatial distances with variable temporal IOIs are presented, the distances are judged to be different according to the temporal IOIs. Helson (1931) called this phenomenon the "Tau effect." Conversely, when temporal IOIs are constant and spatial distances are variable, temporal judgments vary according to the spatial pattern. This phenomenon was called the "Kappa effect" by Cohen, Hansel, and Sylvester (1953), although the phenomenon had previously been reported by Benussi (1913) and Abe (1935). These effects have been found for various modalities (see Jones and Huang, 1982 for an overview).

Most studies on auditory modality have equated the pitch space with ambient space and confirmed that Tau and Kappa effects occur between perceived temporal and pitch intervals (see ten Hoopen, Miyauchi, and Nakajima, 2008 for an overview). However, auditory-motion perception of a moving sound source does not pertain to pitch space but rather to ambient auditory space. It is thus a very interesting question whether the interdependence between temporal variations and ambient spatial variations, not pitch variations, can be found when successive sounds differ in location. Sarrazin, Giraudo, and Pittenger (2007) recently demonstrated that variable IOIs of a sound sequence affect the reproduction of constant distances (Tau effect) and conversely variable spatial distances of a sound sequence affect constant time intervals (Kappa effect). Grondin and Plourde (2007) found that there are conditions under which increasing the spatial distance between sound sources increases the perceived duration of a temporal interval (Kappa effect). The findings by Sarrazin et al. and Grondin et al. indicate that time and space are interactive in auditory perception, memory, cognition, and reproduction. However, they used complex spatio-temporal sequences of sounds. To obtain direct evidences of perceptual interactions between temporal and spatial information in auditory modality, it is necessary to conduct experiments using a simpler sound sequence.

The purpose of the present study was to investigate whether or not temporal variations affect the experience of spatial variations. In the present experiments, sequences consisting of three successive sound bursts (in order of S_1, S_2, and S_3) presented from different loudspeakers were used as the stimuli. The sequence included two IOIs (t_1 and t_2) and two spatial distances (d_1 and d_2) delimited between S_1 and S_2, and between S_2 and S_3. In Experiment 1, participants judged the difference between d_1 and d_2 in various combinations of t_1 and t_2, and d_1 and d_2. In Experiment 2, we measured the perceptual location of S_2 with various temporal and spatial patterns.

EXPERIMENT 1

Methods

Participants: Seven males and one female (aged between 21 and 33) took part in the experiment. One of the males was one of the authors and the other participants were naive regarding the configuration of the stimulus and the objective of the experiment. All had normal hearing (confirmed by audiometric testing).

Apparatus: Each participant sat on a chair located at the center of a circular array of loudspeakers with a radius of 1.5 m in an anechoic chamber (noise level of 19.5 dB). The position of their heads was fixed straight ahead (0°) by a headrest. The array at eye level in the horizontal plane consisted of a series of 36 loudspeakers (Fostex FE83E) installed in a custom-made cylindrical box separated by 10° intervals. Eleven loudspeakers located between −60° and 60° were used in the experiment (Fig. 1). The participants were blindfolded so that they could not see the loudspeakers during the experiment.

Auditory stimuli were computer generated (sampling frequency of 48 kHz and quantization of 32 bits) and presented via the loudspeakers to the participants through a D/A converter (Pavec MD-8D72-133) and amplifiers (Biamp MCA8050). The levels of the sound bursts from all loudspeakers at the head position of participants were calibrated with a measuring amplifier (Brüel & Kjær 2610) and a microphone (Brüel & Kjær 2669 and 4165).

Stimulus: A stimulus pattern consisted of three successive sound bursts (i.e., in order to S_1, S_2, and S_3) presented from different loudspeakers. The sound bursts were pink noise low-pass filtered at 12 kHz. Each sound burst had a duration of 50 ms, which included a cosine-shaped rise-and-fall time of 10 ms. The A-weighted sound pressure level was 78 dB (as measured at the head position of participants when sound was presented continuously).

The total duration delimited by S_1 and S_3 was fixed at 360 ms. The IOI between S_1 and S_2 (t_1) varied from 90 to 270 ms in steps of 30 ms, and consequently, the IOI between S_2 and S_3 (t_2) varied from 270 to 90 ms in steps of 30 ms. Thus, the temporal patterns of t_1 and t_2 ($/t_1/t_2/$) were /90/270/, /120/240/, /150/210/, /180/180/, /210/150/, /240/120/, and /270/90/ [ms]. The loudspeakers presenting S_1, S_2, and S_3 were horizontally changed from the left to the right or from the right to the left. These three loudspeakers were located on the left of the hemisagittal plane (Fig. 1a), on its right (Fig. 1c), or centered across it (Fig. 1b). The angular distances between the two loudspeakers presenting S_1 and S_2 (d_1), and S_2 and S_3 (d_2) were 20° and 40°, 30° and 30°, and 40° and 20°. Thus, the spatial patterns of d_1 and d_2 (d_1:d_2) were 1:2, 1:1, and 2:1 (see Fig. 1). In total, there were 126 stimulus patterns [7 temporal patterns × 3 spatial patterns × 3 spatial locations (left, center, and right) × 2 directions of movement (left-to-right and right-to-left)].

Procedure: All 126-stimulus patterns were presented in random order in each session and they started with four warm-up trials. Each participant performed in nine sessions over three days. The first session served as training. The data obtained in the training session and the warm-up trials were excluded from the final analyses. A two-alternative forced-choice (2AFC) method was employed. Participants were instructed to push a "left" or "right" key according to which of the neighboring two angular distances, they perceived to be closer.

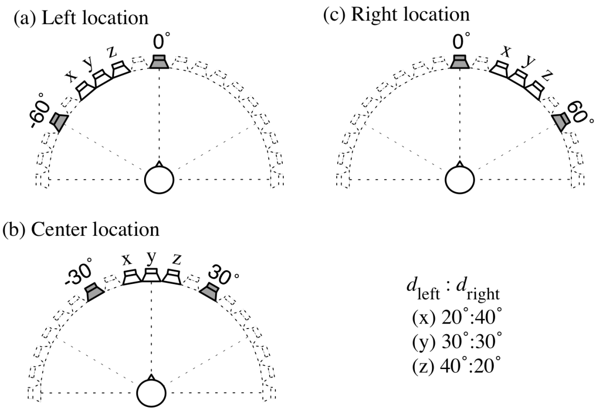

Figure 1. All spatial conditions defining factors of spatial patterns and spatial locations.

Results

The proportion of responses starting that the distance between S_1 and S_2 (d_1) was shorter than that between S_2 and S_3 (d_2) (i.e., $P_{(d_1<d_2)}$) was calculated. Differences of $P_{(d_1<d_2)}$ between spatio-temporal conditions were evaluated using a four-way repeated-measured analysis of variance (ANOVA) with factors related to temporal pattern (t_1:t_2), spatial pattern (d_1:d_2), spatial location (left, center, and right), and direction of movement (right-to-left and left-to-right). The temporal and spatial patterns were found to have significant effects [$F(6, 42) = 26.784$ for temporal pattern and $F(2, 14) = 23.654$ for spatial pattern], while spatial location, direction of movement, and interactions had no significant effects. Thus, the factors of spatial location and direction of movement were merged, and $P_{(d_1<d_2)}$ was plotted as a function of the temporal pattern (i.e., t_1:t_2) with error bars indicating standard errors (see Fig. 2). These results indicate that $P_{(d_1<d_2)}$ decreases as t_1 increases, and consequently, as t_2 decreases. That is, the distance between two sounds closer in time is perceived to be closer in space. The same tendency was found for all spatial patterns and locations. The results clearly demonstrated that the Tau effect between time and ambient space occurred in auditory modality.

Discussion

If variations in a *physical* temporal pattern affect the experience of ambient space, d_1 and d_2 should be perceived as equal when t_1 is equal to t_2. However, our results revealed that when t_1 was about 60 ms shorter than t_2 (i.e., t_1:t_2 = 5:7), d_1 and d_2 were perceived as equal (see the results indicated by the open triangles and solid line in Fig. 2). Nakajima, ten Hoopen, Hilkhuysen, and Sasaki (1992) demonstrated that when two neighboring empty time intervals (t_1 and t_2) composed of three brief successive sounds were presented from a single source, t_2 was perceived to be much shorter than the physical interval because t_2 was perceptually "shrunk" by adding t_1 (Nakajima, ten Hoopen, & van der Wilk, 1991; Nakajima et al., 2004). This illusory phenomenon in regard to auditory-time perception, called "time-shrinking," typically occurs when t_2 is longer than t_1 and when the difference between t_2 and t_1 is less than about 100 ms ($0 < (t_2 - t_1) < 100$ [ms]]. Under the time conditions to meet this range, t_1 and t_2 were perceived to be the same duration (ten Hoopen et al., 2006; Sasaki, Nakajima, & ten Hoopen, 1998; Miyauchi &

Nakajima, 2007). The midpoint of this 1:1 temporal category (i.e., $t_2 - t_1$ = 50 [ms]) and the temporal pattern in which d_1 and d_2 are perceived as equal (i.e., $t_2 - t_1$ = 60 [ms]) is almost the same. These findings suggest that the experience of auditory space is affected by the *perceptual* temporal variations consisting of that space.

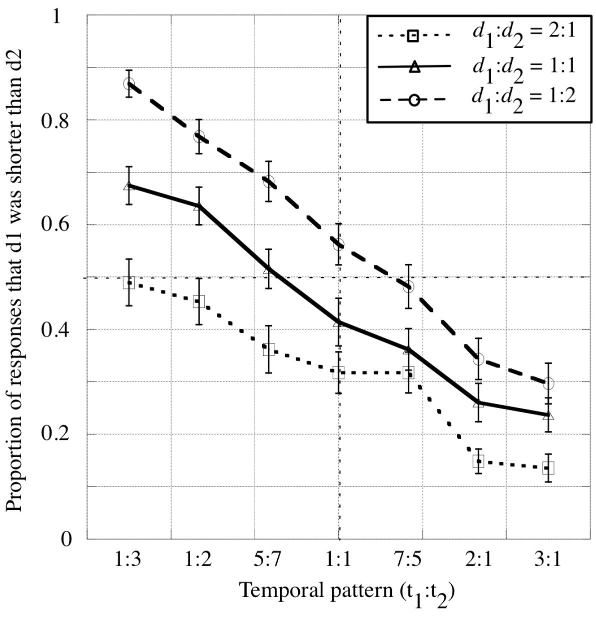

Figure 2. Relationship between factors in Temporal and Spatial patterns.

Sarrazin et al. (2004 and 2007) observed Tau and Kappa effects by using memory and reproduction tasks on visual and auditory modalities. Combinations of spatio-temporal constancy and inconstancy concerned the appearance of Tau and Kappa effects in the formation of the representations of a stimulus sequence in short-term memory. Their results indicated that the Tau and Kappa effects appear when either the space or time to be reproduced is variable while the other is constant. When constancy is counterchanged (i.e., the reproduced domain is constant while the other is variable), these effects disappear. Moreover, these effects were not observed with-in the combination of variable-temporal and variable-spatial patterns. They claimed that dimensional interference in an auditory memory only occurred when the relevant dimension was constant. Our present results demonstrate that the value of $P_{(d_1<d_2)}$ linearly decreases with variations in the temporal pattern. This means that even when the relevant time dimension is variable, the impression of the spatial pattern is affected by variations in the temporal pattern. For example, when d_1: d_2 was 2:1 and t_1: t_2 was 1:2 or 1:3, the d_1 was perceptually shorter than d_2. These findings indicate that temporal variations have a strong effect on the formation of the perceptual spatial pattern. This difference between perception and memory may give clues to improved understanding of the links between them.

EXPERIMENT 2

The results from Experiment 1 clearly demonstrated that the Tau effect between time and ambient space occurred in auditory modality. However, it remains unclear whether the temporal pattern affects the ability to localize each sound or to organize some sound into a spatial pattern. In Experiment 2, we measured the absolute perceptual locations of S_2 under four conditions, (1) S_2 was presented alone, (2) S_1 was presented before S_2, was presented (3) S_3 was presented after S_2, was presented and (4) S_1, S_2, and S_3 were sequentially presented. The perceptual location of S_2 was only varied according to the temporal pattern under condition (4) if time patterns affect the sound localization.

Methods

Participants: A male and a female took part in the experiment. They were naïve regarding the configuration of the stimulus and the objective of the experiment and they had normal hearing (confirmed by audiometric testing).

Apparatus: Each participant individually sat on a chair located at the center of a semicircular array (radius of 1.1 m) of loudspeakers in a sound-proof room. Their heads were fixed in a straight-ahead position (0°) by a chin rest. The array at eye level on the horizontal plane consisted of a series of 19 loudspeakers (Hoshiden 7N101; φ = 30 mm), mounted in a custom-made enclosure and separated by 2.5° intervals.

Stimulus: All sound bursts used in the experiment were 1-kHz pure-tone bursts and they had a duration of 10 ms, which included cosine-shaped rise and fall time of 5 ms. We prepared four types of stimulus patterns, i.e., S_2, S_1–S_2, S_2–S_3, and S_1–S_2–S_3 conditions. Under the S_2 conditions, a single sound burst (S_2) was presented by itself from one of six loudspeakers located at –12.5º, –7.5º, –2.5º, 2.5º, 7.5º, and 12.5º. Under the S_1–S_2 conditions, a sound burst (S_1) was presented from the loudspeaker located at –15º before S_2 was presented. The time interval between S_1 and S_2 (t_1) was 120, 180, or 240 ms. Under the S_2–S_3 conditions, a sound burst (S_3) was presented from the loudspeaker located at 15º after S_2 was presented. The time interval between S_2 and S_3 (t_2) was 120, 180, or 240 ms. Under the S_1–S_2–S_3 conditions, three sound bursts, S_1, S_2, and S_3, were sequentially presented. The temporal patterns of these sound bursts ($/t_1/t_2/$) were /120/240/, /180/180/, and /240/120/ ms. In total, there were 6 (6 locations of S_2 × 1 time variation), 18, 18, and 18 (6 locations of S_2 × 3 time variations) stimulus patterns uder respective S_2, S_1–S_2, S_2–S_3, and S_1–S_2–S_3 conditions.

Procedure: The participants were instructed to concentrate on a fixation line located at a position that was straight-ahead (0º) of them during the experiment. Each participant's task was to judge the perceived location of S_2 relative to the fixation line and to push a "left" or "right" key according to whether S_2 was located at left or right of the fixation line. Each participant took part in 14 trials for each stimulus pattern.

Results

We first calculated the proportion of judgments in which the participant judged the sound as being presented from the left of the fixation line. We then fitted logistic functions, by using the maximum-likelihood method (Wichmann and Hill, 2001), to the response distributions as a function of the location of S_2 relative to the fixation line under all temporal and spatial conditions. The results obtained under the S_1–S_2, S_2–S_3, and S_1–S_2–S_3 conditions are in Fig. 3. The results under S_2 conditions have been given in all panels as a reference.

The point of subjective equality (PSE), defined as the 0.5-point on the psychometric function, was estimated from the fitted psychometric functions for each indivisual participant. The PSE indicates the relative position of the loudspeaker at which the sound was perceived at the same location as the fixation line. The PSE under S_2 conditions, in which S_2 was presented alone, was –1.4º. We defined the PSE under S_2 conditions as the reference perceptual location of participants without the influence of other sounds, and calculated the disparities in PSEs between S_2 and the other conditions (Table 1).

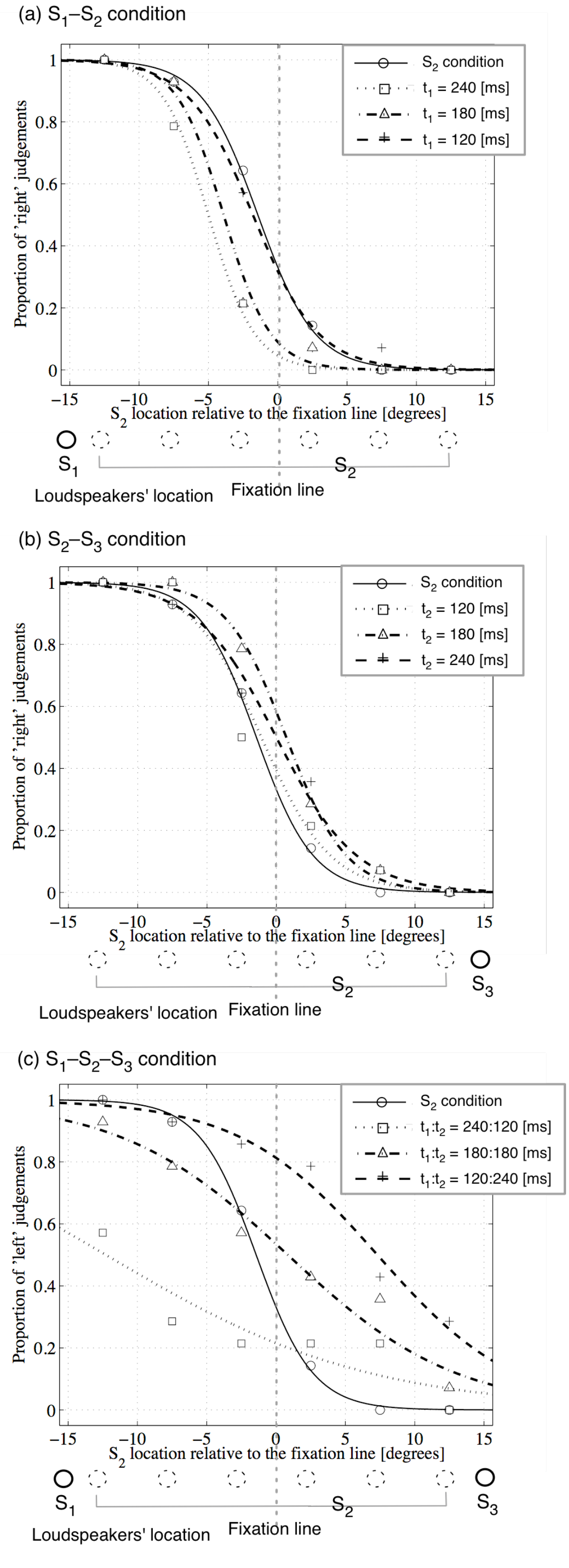

Figure 3. Proportion of left judgements and phychometric function fitted to this proportion.

Discussion

Under S_1–S_2 conditions (Fig. 3(a)), the disparities in PSEs between S_2 and S_1–S_2 conditions were negative values (Table 1). This means that the perceptual location of S_2 had slightly shifted to the right under the influence of S_1 presented at left of S_2. On the other hand, in S_2–S_3 condition (Fig. 3(b)), the disparities in PSEs between the S_2 and S_2–S_3 conditions were positive values (Table 1). This means that the perceptual location of S_2 had slightly shifted to left under the influence of S_3 presented at right of S_2. These results indicate that S_2 was mislocated in the direction opposite to the preceeding or following sound. In other words, the spatial disparity between two sequencial sounds was underestimated.

Table 1. Disparity in PSEs between S_2 and other conditions.

	/120/240/	/180/180/	/240/120/
S_1–S_2	–0.7º	–2.7º	–3.4º
S_2–S_3	1.4º	2.2º	0.2º
S_1–S_2–S_3	8.5º	2.9º	–10.1º

Under S_1–S_2–S_3 conditions (Fig. 3(c)), the perceptual location of S_2 strongly depended on the temporal patterns. When t_1 was shorter than t_2 (/120/240/), the PSE drastically shifted to the right as 8.5º. This means that the perceptual location of S_2 shifted to the left under the influence of S_1 and S_3 (Fig. 4(a)). Under these conditions, the time interval consisting of S_1 and S_2 was shorter than that consisting of S_2 and S_3. Thus, the results indicate that the spatial disparity presented with shorter time intervals was underestimated, and/or conversely, the spatial disparity presented with longer time intervals was overestimated. This tendency was the same as that in the findings in Experiment 1.

However, when t_1 was longer than t_2 (/240/120/), PSE drastically shifted to the left as –10.1º. This means that the perceptual location of S_2 shifted to the left under the influence of S_1 and S_3 (Fig. 4(b)). This indicates the same tendency as that for the /120/240/ temporal pattern in that the spatial disparity presented with shorter time intervals was underestimated, and/or conversely, the spatial disparity presented with longer time intervals was overestimated.

Note that the slopes for psychometric functions under S_1–S_2–S_3 conditions were clearly gradual rather than those under the other conditions (Fig. 3). This indicates that the accuracy of sound localization decreased in the complex sound sequence.

The extreme mislocalization of S_2 under S_1–S_2–S_3 conditions was not solely attributed to the presentation of either a preceding (S_1) or following (S_3) sound, because the results under S_1–S_2 and S_2–S_3 conditions indicated that the effect of presentation of either S_1 or S_3 was to shift S_2 in the direction opposite to these sounds, and the values for this effect were less than 3.4º. S_2 was drastically mislocated only when three sounds were successively presented, i.e., only when a temporal pattern consisting of two or more time intervals was perceived. The perceptual location of S_2 was strongly influenced by the temporal pattern, and the auditory Tau effect demonstrated in Experiment 1 might have been caused by the mislocalization of S_2.

CONCLUSIONS

The results presented in this report demonstrate that the auditory Tau effect occurs when a simple sequence consisting of three sounds (which was more commonly used in earlier studies on other modalities) was used. The *perceptual*, not physical, temporal pattern affects the experience of auditory ambient space. This illusory phenomenon might be caused by the mislocalization of S_2. To further understand the interactive interference between time and space in auditory modality, the results of the present study need to be analyzed further to determine what effect spatial variations have on the perceptual organization of temporal patterns.

We believe that the dramatic effect of a temporal pattern on spatio-temporal interference rather than that of other modarlities can be attributed to the superiority of auditory modality in the time domain. The total IOI of the sound sequence used in the present experiment was 360 ms. Under shorter temporal conditions, the perceptual connection of these sounds in the temporal domain is indivisible. However, there is no evidence that shows how the spatial information on successive sounds is integrated into a sequential spatial pattern or a moving pattern. To discuss the asymmetrical effect on the interactive interference between time and space, we need to study what effect variations in spatial patterns have on the experience of the temporal pattern.

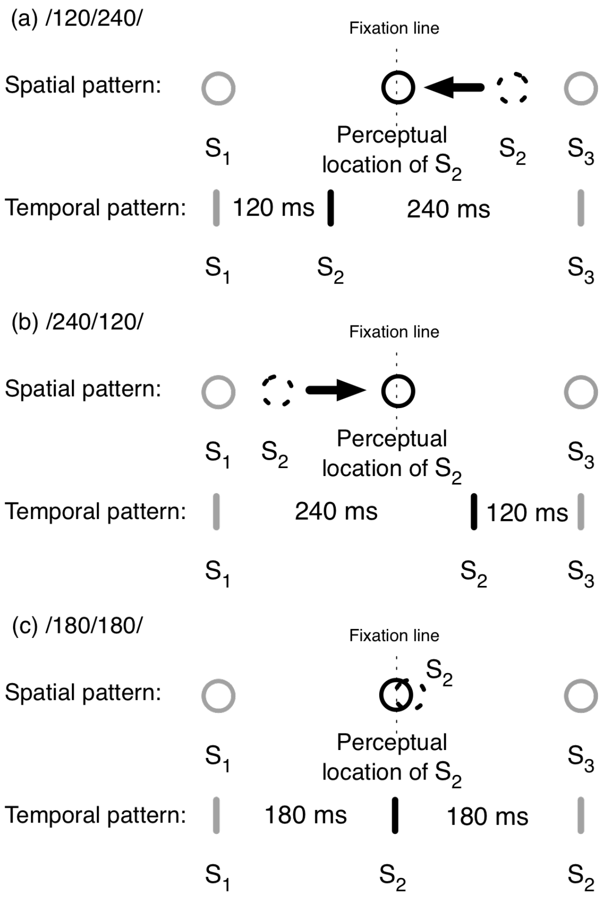

Figure 4. Diagram of results under S_1–S_2–S_3 conditions. Dotted circle indicates physical location of S_2. Solid circles indicate perceptual locations of S_2.

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