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The effect of phasic alertness on temporal precision

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Abstract Many previous studies have found that there is a close relationship between attention and temporal precision. As a mechanism that regulates the intensity of attention, alertness has beneficial influences on perceptual processing. However, little is known regarding whether and how phasic alertness affects temporal precision. Experiment 1 and Experiment 2 used visual and auditory warning cues in a visual temporal order judgment (TOJ) task and a simultaneity judgment (SJ) task to investigate the phasic alerting effect on temporal precision. Participants in the TOJ and SJ tasks were required to make judgments of two successive and synchronous stimuli at various stimulus onset asynchronies (SOAs). Because of dissension regarding the SJ task, Experiment 3 adopted a dual SJ and TOJ task to create a new indicator of participant performance. Although these tasks may differ in the cognitive mechanism they involve, they all produced consistently decreased just noticeable difference (JND) scores and unaltered point of subjective simultaneity (PSS). This suggests that phasic alertness could significantly improve participants' temporal precision (reduced JNDs) of visual perception, without affecting temporal accuracy (unaltered PSS). We then discuss that the alerting effect on temporal sensitivity might be attributed mainly to transient arousal rather than temporal expectancy. Furthermore, the analysis of response ratios at each SOA could distinguish a heightened temporal precision from a reduction of attentional lapses. According to the previous and present studies, phasic alertness might simultaneously benefited the early perceptual processing and late motor execution of responses.

Keywords Phasic alertness · Temporal precision · Warning cues · TOJ and SJ tasks

Time perception is fundamental to our experience and central to virtually all activities. Relative to physical time, our perception of time could be modulated by changes in environmental context and personal characteristics. Temporal precision refers to the discrimination ability of the visual system and can be considered in terms of the temporal sensitivity of our perceptual processing (Yeshurun & Levy, 2003). Participants with high temporal precision can distinguish the relative temporal occurrence of closely occurring events and resolve temporal details in the visual and auditory fields. Many circumstances in our daily lives, such as driving on a busy highway, participating in an intense sports competition, and listening to a complex speech, involve discerning information so rapidly that it is measured on a scale of tens or hundreds of milliseconds. Fine temporal precision of perception is critical for secure and successful performance in these circumstances and can help precisely represent the dynamic structure of our living environment. Therefore, it is important to explore what factors influence temporal precision.

The role of attention mechanisms is a fundamental issue in contemporary research on timing and time perception (Brown & Boltz, 2002; Buhusi & Meek, 2009; Hemmes, Brown, & Kladopoulos, 2004). Many studies have investigated the relationship between attention and temporal precision in visual perception. Previous research has indicated that spatial attention could enhance the temporal precision of visual perception with stimuli appearing at cued as opposed to uncued locations (Boet, Poon, & Yu, 2001; Chica & Christie, 2009). Correa,

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Sanabria, Spence, Tudela, and Lupiáñez (2006) also found that selective temporal attention could improve the temporal precision of visual perception. This facilitating influence of attention on temporal information processing has become known as prior entry (Stelmach & Herdman, 1991; Weiss & Scharlau, 2011, 2012). However, prior entry could be attributed to the orienting system of the attentional network, in which external cues provide temporal or spatial information, and result in higher temporal sensitivity of an attended stimulus or position (Mahoney, Verghese, Goldin, Lipton, & Holtzer, 2010; Posner & Petersen, 2012). Most studies of temporal perception focus on the effect of orientation of attention. The influence of alertness on temporal perception, however, is still unclear.

In everyday life, salient stimuli, such as a buzz from a text message, a change of traffic light color, or a signal from the natural environment (i.e., thunder, lightning), alert us and enhance our arousal. In the present study, we introduce this special attentional state called alertness. It is one of three distinct attentional networks proposed by Posner and colleagues (1971), which carries out stimulus recognition and response initiation (Fan, Mccandliss, Fossella, Flombaum, & Posner, 2005; Mahoney et al., 2010; Posner & Boies, 1971; Posner & Peterson, 1990). Orienting is the most studied attentional network, which focused on the ability to prioritize sensory input by selecting a modality or location among multiple sensory stimuli. As a basic intensity aspect of attention, alertness could arouse the physical and cognitive system for a general level of response readiness by means of self-initiated preparation or external signals that indicate imminent occurrence of the target stimuli (Callejas, Lupiàñez, Funes, & Tudela, 2005; Funes, Lupiáñez, & Milliken, 2007; Posner & Petersen, 2012; Sturm & Willmes, 2001). Consequently, two types of alerting systems have been described. Tonic alertness refers to a top-down sustained activation over a period of several minutes, whereas phasic alertness is a non-specific activation occurring when an external warning cue is presented a few hundred milliseconds prior to the target (Callejas et al., 2005; Raz & Buhle, 2006; Sturm & Willmes, 2001).

According to the latest theoretical model of cognitive control (Sadaghiani & Kleinschmidt, 2016), tonic alertness is described as the mentally effortful, self-initiated (rather than externally driven) preparedness to resolve information and to respond. However fast-changing and stimulus-driven phasic alertness is considered part of phasic adaptive control, which refers to the coordination of goal-relevant information across subprocesses and the dynamic adaptation of this coordination. Phasic alertness could entail keeping distributed contextual and stimulus-related information online under achieving set-shifting or cognitive flexibility. Its adaptive nature can be observed during exogenously triggered initiation of control by external alerting cues, adaption of behavior after errors (Dosenbach et al., 2007), and moment-to-moment adjustment of control in repeated rapid task-switching (Seeley et al., 2007). Previous researchers often manipulated phasic alertness with infrequent, unpredictable warning cues preceding the presentation of target stimuli, such as visual and auditory external cues (Liu et al., 2014), presenting a prominent frame around fixation (Matthias et al., 2010), or changing the colors of the experimental background (Wang, Zhao, Xue, & Chen, 2016).

In the present study, the alerting system mentioned is specific to phasic alertness. Previous studies reported that faster RTs and improved response accuracy of simple responding or detection tasks were observed following the warning cue compared with the no cue condition. Most researchers indicated that the alerting effect could facilitate early perceptual encoding stage (Correa et al., 2006; Rolke & Hofmann, 2007) and stimulus-triggered visuo-motor response activation (Fischer, Plessow, & Kiesel, 2012) or late motor execution (Fecteau & Munoz, 2007; Hackley & Valleinclán, 2003; Weinbach & Henik, 2012). Data also have shown that stimulus detection and discrimination can be enhanced by warning signals, which inform participants that target stimuli are imminent and allow attentional preparation (Hackley & Valleinclán, 2003; Posner, 1978). Thiel, Zilles, and Fink (2004) provided neural evidence that phasic alertness could increase activity in the extrastriate cortex. This region is more intimately involved in both perceptual and enhanced stimulus extraction and encoding, as opposed to being involved only in motor actions. Although alerting signals provide little information about features of the target stimulus and required response, the alerting effect conferred a behavioral and cognitive advantage over conditions without warning signals (Coull, Nobre, & Frith, 2001; Yanaka, Saito, Uchiyama, & Sadato, 2010).

The majority of prior research has used the temporal order judgment (TOJ) task to investigate the temporal precision of perception. When performing the TOJ task, stimulus pairs are presented at various stimulus onset asynchronies (SOAs), and participants are required to judge which of two stimuli occurred first. The present study used the TOJ task in Experiment 1. In Experiment 2, we employed the simultaneity judgment (SJ) task, requiring participants to judge whether two target stimuli were simultaneous or asynchronous (Parise & Spence, 2008; Shore, Spence, & Klein, 2001; Spence, Charles, 2009). Although the two experimental procedures were the same except for their instructions, it is worth noting that some researchers assert that TOJ and SJ tasks differ in the cognitive mechanism they involve (van Eijk, Kohlrausch, Juola, & van de Par, 2008; Garcíapérez & Alcaláquintana, 2012; Love, Petrini, Cheng, & Pollick, 2013). In Experiment 3, a dual SJ and TOJ task were performed to clear up the controversy surrounding SJ. Participants were required to answer successively an SJ and TOJ question to create a new index of temporal precision. Beyond that, we adopted relatively salient warning cues in both the auditory and visual modalities to investigate the effect of alertness on the temporal precision of visual perception. We implemented the TOJ task in Experiment 1 and the SJ task in Experiment 2, together with a dual task in Experiment 3 to affirm the reliability of our experimental result.

Experiment 1

Method

Participants

A power analysis (Faul, Erdfelder, Lang, & Buchner, 2007) indicated a sample of 12 to have adequate power ($1-\beta \geq 0.80$) to detect a large effect ($\eta^2_p = 0.40$). A group of 31 right-handed undergraduate and graduate students (15 female, ages 18-24 years, mean age = 19.8 years) from Southwest University of China were recruited for Experiment 1. According to the fitting coefficient (R^2) of each block of participant's data, six participants were excluded for failure to do the task properly ($R^2 < 0.75$). All participants had normal or corrected-to-normal vision, normal hearing, and no neurological or psychiatric antecedents. At the end of the experiment, they received payment for their participation.

Stimuli and apparatus

The targets were two brief green and red dots (0.5°× 0.5° visual angle), presented randomly at four (top, down, left, right) different positions with 8° visual angle from fixation on a black background. The fixation point consisted of a centrally presented white fixation cross (0.5°× 0.5° visual angle). The warning cues were composed of a two-channel modality and distributed in two blocks. The visual warning cue was a yellow lightning signal (1.2°×1.2° visual angle), which appeared centrally, preceding presentation of the target stimuli. The auditory warning cue was a pure tone (1,000 Hz, 50 dB), delivered via the EDIFIER K815 headphone. In the no-cue condition, the screen remained fixed for the same amount of time as in the alerting condition. All stimuli were presented to participants from a distance of 55 cm and at approximately eye level. E-Prime 1.0 software was used for programming and timing operations. The data were collected and the stimuli were presented using a P76f+ Pro computer with an Intel Core5 HD3470, 3.2GHz, and a 17" monitor (1,024 × 768 pixel screen resolution, 75-Hz refresh rate). Participants entered their responses on a computer keyboard in a soundproof cubicle.

Design and procedure

Target stimuli were timed to appear randomly at four peripheral positions around a central fixation point on the computer screen and distributed to visual and auditory blocks in a random sequence. For half of the trials, the warning cue would appear, and for the remaining half, there was only fixation. Among all of the trials, target occurrence included green-first (SOA = −104 ms, −78 ms, −52 ms, −26 ms), red-first (SOA = 26 ms, 52 ms, 78 ms, 104 ms), and the two dots occurring synchronously (SOA = 0 ms). Synchronous trials allowed us to assess the point of subjective simultaneity (PSS), whereas asynchronous trials were used to test whether participants could perform temporal order judgment accurately. Each trial started with presentation of the fixation cross (1,000 ms). Later, the warning cue was presented for 200 ms. After a random delay (50~500 ms), a fourth panel with target stimuli was presented. Participants were required to judge which of two stimuli had occurred first by pressing one of two response keys on the computer keyboard ("q" or "p," operated with the left-hand and the right-hand, respectively) during the response period (3,000 ms). There was a random interval (1,000~1,500 ms) before the beginning of the next trial. Participants were instructed to maintain their gaze at the central fixation figure throughout the duration of the experimental procedure. They were informed that warning cues would appear randomly, indicating that the target stimuli would immediately follow. One experimental session consisted of two blocks of 224 trials each, with a 2-minute rest between blocks (Fig. 1). Participants were easily tired due to concentrating on the task, so we set a 1-minute rest in the middle of each block.

Results

Researchers typically analyze participants' performance by fitting a Gaussian function and a cumulative Gaussian function to the simultaneous and asynchronous response data in SJ

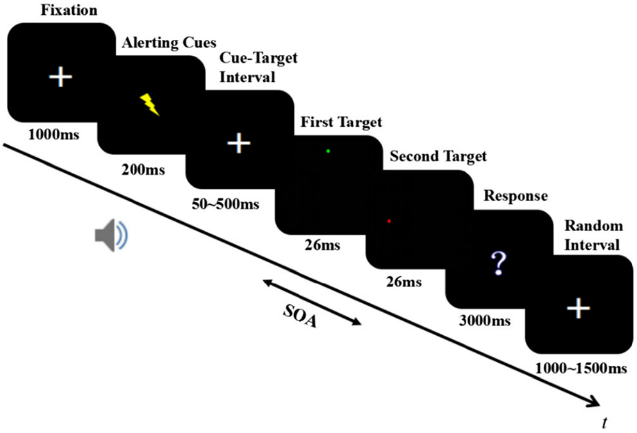

Fig. 1. Experimental sequence. The tasks (TOJ and SJ) comprised two blocks. Above, the procedure line indicates a visual block with a visual warning cue. Below is an auditory block, with a warning cue comprised of a pure tone. Participants were required to judge the targets' temporal order (Which came first?: red first vs. green first) in each trial of the TOJ task. In contrast, SJ participants were asked to judge simultaneity (synchronous or asynchronous).

and TOJ tasks respectively. There are two key performance parameters that can be estimated from the fitting curve. The first is the amount of time by which one stimulus must precede (or follow) the other for the two stimuli to be perceived as simultaneous, known as the point of subjective simultaneity (PSS). This value reflects an estimate of the center of the Gaussian distribution, at which point participants would be likely to make each response equally often (Spence & Parise, 2010). The PSS corresponds to the SOA at which the proportion of responses is 50% and represents the temporal accuracy of judgment relative to a veridical standard (Eskes, Klein, Dove, Coolican, & Shore, 2007). The second is the just noticeable difference (JND), defined as the smallest temporal interval between the onset of two stimuli needed for participants to perceive the correct order. It has conventionally been calculated as half the temporal interval between the 25% and 75% points on the cumulative Gaussian psychometric function. A steep psychometric curve can indicate a small JND, which implies a high temporal sensitivity and fine temporal precision (Eskes et al., 2007; Seifried, Ulrich, Bausenhart, Rolke, & Osman, 2010; Vroomen & Keetels, 2010). In this case, even small asynchronies can be correctly perceived by participants.

Estimation of PSS and JND

To estimate the PSS and JND values for each participant and cue-condition, we computed the proportion of "red dot presented first" responses at each SOA level. MATLAB Statistics and Curve Fitting Tools were used for the statistics calculation and graphic presentation of the results. We followed the conventional calculation of JND (half the temporal interval between the 25% and 75% of judging the red dot first) and PSS (50% proportion of judging the red dot first) and then ran a repeated measures analysis of variance (ANOVA) on the proportion of response data using cue condition (cue vs. no cue) and channel (visual vs. auditory) as factors. The analysis of PSS revealed no significant effect of cue [$F(1, 24) = 4.030, p > 0.05, \eta^2_p = 0.144$], as the PSS in trials was not affected by warning cue nor by channel [$F(1, 24) = 0.057, p > 0.05, \eta^2_p = 0.002$]. In addition, there was no significant interaction between cue and channel [$F(1, 24) = 1.607, p > 0.05, \eta^2_p = 0.063$]. The results pertaining to the JND demonstrated a significant difference between the alerting cue condition and the no cue condition [$F(1, 24) = 37.132, p < 0.001, \eta^2_p = 0.607$].

We conducted logistic regressions using a generalized linear model with the response ratios of judging red first for each SOA condition. In Fig. 2, the left negatives represent the red dot following the green dot. The curves show that visual and auditory alerting cues make the proportion of judging red first obviously below that of the no cue condition. The right positives represent the red dot preceding the green, and the alerting curves are significantly higher than the curves for no visual or auditory cues. We then computed a paired-sample *t* test (one-tailed) of response ratios at every SOA. After Bonferroni correction for multiple comparisons, there was a significant difference between the visual cue and no cue conditions for SOA = ±78 ms, ±52 ms, −26 ms, 0 ms ($ps \leq 0.0056$). Whereas under the auditory condition, there was a significant difference between the cue condition and the no cue condition for SOA = ±78 ms, ±52 ms, ±26ms ($ps \leq 0.0056$). These results imply that participants responded more precisely for pairs of targets appearing under the alerting condition than for pairs appearing under the no-alerting condition.

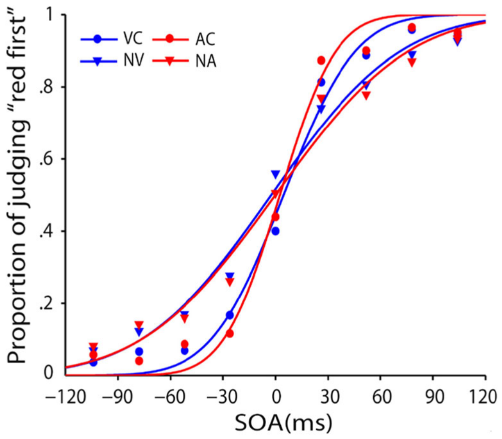

Fig. 2. From the data of TOJ tasks, the proportion of "red first" responses at each SOA level was fitted with a Gaussian cumulative distribution function. *VC* visual cue; *NV* no visual cue; *AC* auditory cue; *NA* no auditory cue. Negative values represent the red dot following the green dot, and positive values represent the red dot preceding the green.

Reaction times

Figure 3 shows that RTs decrease gradually with growing SOAs under conditions with and without alerting cues. We computed a paired-sample *t* test (one-tailed) of RTs. After Bonferroni correction for multiple comparisons, results indicated a significant difference between the visual cue condition and the no-cue condition for SOA = 26, 52, 78, 104 ms ($ps \leq$

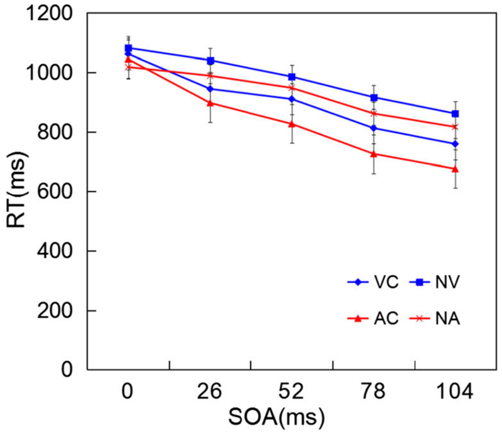

Fig. 3. Reaction times for TOJs.

0.01). Whereas the results under auditory condition were the same as under the visual condition, SOA = 26, 52, 78, 104 ms showed a significant difference (*ps* ≤ 0.01). These results imply that phasic alertness in the auditory and visual modalities could decrease participants' response times.

Discussion

The purpose of Experiment 1 was to examine the effect of phasic alertness in the visual and auditory modalities on temporal precision of visual perception. Two measures were derived from the TOJ task. The results of Experiment 1 demonstrated that alerting cues can reduce JND scores ($\mathrm{JND_{vc}}$ = 21.69 ms, $\mathrm{JND_{ac}}$ = 18.15 ms) compared with the no-cue condition ($\mathrm{JND_{nv}}$ = 38.97 ms, $\mathrm{JND_{na}}$ = 40.45 m). Smaller JND scores mean higher temporal precision (Eskes et al., 2007; Seifried et al., 2010; Vroomen & Keetels, 2010). The decreased JNDs under alerting condition showed that phasic alertness could enhance participants' visual temporal precision. Furthermore, no significant interaction was found between cue and channel, which indicates that there was no prominent difference between visual and auditory cues on enhancing temporal precision in the visual temporal order tasks. As we expected, the PSS did not change significantly, which may indicate that warning cues did not significantly affect participants' temporal accuracy. This result could be attributed to the characteristics of the warning cues, which did not provide temporal or spatial information about the targets or specific responses. The result of the response ratios test at short and medium SOAs (26, 52, 78 ms) indicated that visual and auditory phasic alertness specifically improved the precision of visual temporal perception. When SOA = 0 ms, the red and green dot appeared at the same time, forcing participants to make an uncertain choice and resulting in their response proportion approaching 0.5. When SOA = ±104 ms, it seemed that the temporal difference between targets was significant enough for participants to easily make correct judgment, and the alerting effect on response precision decreased. Funes, Lupiáñez, & Milliken (2007) found that cue-target SOA could modulate the magnitude of the phasic cueing effect, especially a pronounced reduction of spatial Stroop effect at short SOAs that diminished at longer SOAs. Koppen and Spence (2007) employed a TOJ task to investigate the Colavita visual dominance effect. They also found that no Colavita effect was observed at the larger SOAs where participants could perceive the correct order. Furthermore, the alerting effect has typically been evaluated by measuring reaction times to targets preceded by warning signals as opposed to those without warning cues. The results pertaining to RTs showed a fast and short-lived enhancement of perceptual activity and responding speed at all SOAs under alerting conditions. This result indicates that participants under the phasic alerting condition could make precise and quick responses in the visual TOJ tasks.

Experiment 2

To address potential criticism and to verify the effect of phasic alertness on temporal perception from the results of TOJ task, we recruited participants to conduct another experiment based on the SJ task. In a typical TOJ task, participants must judge which stimulus appears first, whereas in the SJ task, they must report whether the target stimuli were presented simultaneously. Although the experimental procedure is the same, SJ and TOJ tasks are underpinned by separate cognitive mechanisms and measure distinct aspects of temporal perception (Nicholls, Lew, Loetscher, & Yates, 2011; Yates & Nicholls, 2011). It should be noted that the JND derived from a cumulative Gaussian function of the TOJ task reflects the steepness of the fitting curve and often is regarded as the minimum SOA (half the temporal interval between the 25% and 75% points) between two targets that allows correct discrimination of temporal order (van Eijk et al., 2008). In the SJ task, the JND derived from a Gaussian function reflects the width of the curve, which is calculated as 75% "simultaneity" responses (equivalent to SD in some studies; Zampini, Shore, & Spence, 2005). The spread of this distribution also provides a measure of participants' sensitivity to asynchrony. Specifically, smaller JNDs indicate steeper psychometric functions and thus better discriminative performance (Spence & Parise, 2010; Zampini et al., 2005). Schneider and Bavelier (2004) found that JND scores were significantly higher for TOJ than SJ tasks, which indicates that participants may find TOJ tasks to be more difficult than SJ tasks for them (Love et al., 2013). Moreover, the consensus is that TOJ and SJ tasks imply different response biases (Spence & Parise, 2010). In other words, temporal order responses must be given (red first or green first) in the TOJ task, so observers would tend to adopt the assumption that stimuli are never simultaneous. However, in the SJ task, observers may be inclined to assume that stimuli belong together, only because the "synchronous" response category is available.

Method

Participants

A power analysis (Faul et al., 2007) indicated a sample of 12 for adequate power ($1-\beta \geq 0.80$) to detect a large effect ($\eta^2_p = 0.40$). A group of 33 right-handed undergraduate and graduate students (16 females, ages ranging from 18 to 24 years, mean age = 19.8 years) from Southwest University of China were recruited for this experiment. Based on the fitting coefficient (R^2) of each block of every participant, four participants were excluded for failure to do the task properly ($R^2 < 0.75$). All participants had normal or corrected-to-normal vision, normal hearing, and no auditory, neurological, or psychiatric antecedents. Participants received payment after participating in the study.

Stimuli and apparatus

The stimuli and apparatus were the same as in Experiment 1.

Design and procedure

The procedure was identical to Experiment 1, except for the instruction that participants had to decide whether the red and green dot, presented randomly on four different positions around fixation, occurred synchronously or asynchronously.

Results

Estimation of PSS and JND

To estimate the PSS and JND for each participant and cue-condition, we computed the proportion of "simultaneity" responses at each SOA level. MATLAB Statistics and Curve Fitting Tools were used for the statistics calculation and graphic presentation of the results. The proportion of simultaneity responses was submitted to a repeated measures analysis (ANOVA) with the cue condition (cue vs. no cue) and channel (visual vs. auditory) as two independent variables. The ANOVA on PSS revealed no significant effect of cue [$F(1, 28) = 1.539$, $p > 0.05$, $\eta^2_p = 0.052$], and the PSS in trials was not affected by warning cue nor channel condition [$F(1, 28) = 0.019$, $p > 0.05$, $\eta^2_p = 0.001$]. In addition, there was no significant interaction between cue and channel [$F(1, 28) = 0.120$, $p > 0.05$, $\eta^2_p = 0.004$]. The results pertaining to JND scores demonstrated a significant main effect of cue condition [$F(1, 28) = 23.015$, $p < 0.001$, $\eta^2_p = 0.451$]. The main effect of channel was not significant [$F(1, 28) = 0.001$, $p > 0.05$, $\eta^2_p = 0.001$], nor was the interaction between cue and channel [$F(1, 28) = 2.528$, $p > 0.05$, $\eta^2_p = 0.083$].

The proportion of responses indicating the simultaneous presentation of red and green dots was calculated for each SOA. Figure 4 shows the peak of the curve representing the proportion of judging simultaneity. It seems that there is no significant difference between the cue and no-cue condition. On both sides of SOA = 0 ms, the negatives and positives respectively represent red or green dots appearing asynchronously. The proportion of responses decreases gradually with growing SOAs, and the visual and auditory alerting curves are below the no-cue condition. We conducted a paired-sample *t* test (one-tailed) of response ratios at every SOA. After Bonferroni correction for multiple comparisons, there was a significant difference between the visual cue and no cue condition for SOA = 78 ms, ±52 ms, −26ms (*ps* ≤ 0.0056), whereas under the auditory condition, only SOA = −104 ms showed a significant difference between the cue and no-cue conditions (*ps* ≤ 0.0056). This suggests that visual alerting improves response precision in the SJ task more than does auditory alerting.

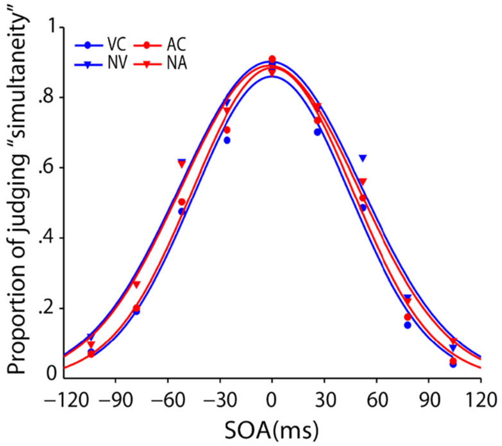

Fig. 4. The proportion of synchronous responses at each SOA level was fitted with a Gaussian probability density function. Psychometric functions were estimated by a Gaussian fitting with the data from SJ tasks. The same is true for TOJ: *VC* visual cue; *NV* no visual cue; *AC* auditory cue; *NA* no auditory cue. Negative values represent that the red dot followed the green dot, whereas positive values represent that the red dot preceded the green.

Reaction times

Figure 5 shows the results of a paired-sample *t* test (one-tailed) of RTs. After Bonferroni correction for multiple comparisons, there was a significant difference between the visual cue and no cue conditions only at SOA = 78 ms (*ps* ≤ 0.01), whereas in the auditory condition, all SOAs showed a significant difference (*ps* ≤ 0.01). This implies that auditory alerting cue decreases response times better than does visual modality.

Discussion

In Experiment 2, we adopted an SJ task that required participants to judge whether red and green dots appeared synchronously or asynchronously. Although the cognitive mechanism in the SJ task is different from that of the TOJ task, the main results of this task were almost consistent with the former TOJ task in Experiment 1. We found smaller JND values under visual and auditory alerting cues condition compared with the no-cue condition [visual: JND = 29.4 ms vs. 34.78 ms; and auditory: JND = 30.22 ms vs. 33.99 ms]. This suggests that phasic alertness can enhance temporal precision on a visual SJ task. The results of PSS show that participants were not obviously biased toward the red or green target, so warning cues did not affect the temporal accuracy. The analysis of responses ratios indicated that the visual alerting effect was

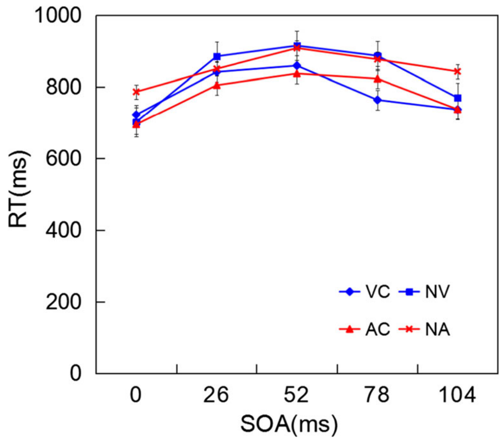

Fig. 5. RTs for the SJ task.

almost consistent with the TOJ task. When the red and green dots appeared simultaneously (SOA = 0 ms), participants in both the cue and no-cue conditions were inclined to judge simultaneity. The proportion of synchronous responses at short and medium SOAs under the visual alerting condition was significantly lower than under the no cue condition, whereas auditory cue produced this effect only at SOA = −104 ms. On the other hand, the results pertaining to the RTs of the SJ task were somewhat different from those of the TOJ task in the alerting modality. The auditory alerting cue at all SOAs clearly decreased reaction time, while the visual alerting cue had this effect only at SOA = 78 ms. The different results of RTs between auditory and visual cues may be due to the experimental paradigm and the characteristics of the channel. Because the SJ task only asked participants to judge whether two dots appeared synchronously or asynchronously, participants did not need to identify the order of the slim temporal difference between the targets (Schneider & Bavelier, 2004). In contrast, the TOJ task required participants to judge which dots appeared earlier, participants had to resolve the temporal detail of targets to make correct responses to the greatest extent possible. Moreover, previous research has indicated that auditory activity is a relatively automatic function, which captures and maintains attention more easily than the visual channel (Penney, 2003). Therefore, participants in the relatively easy SJ task with auditory cue showed a better alerting effect on accelerating speed of temporal perception than those in the visual condition.

Experiment 3

Previous studies have indicated that there are two popular methods for measuring the temporal precision of visual perception. One is to estimate the range of apparent simultaneity by using an SJ task, and the other is to estimate the smallest temporal interval from the slope of the psychometric function of a TOJ task. Some researchers argue that it is misleading to take the PSS as an estimate of the relative timing at which two events seem synchronous. Instead, there is typically a relatively broad range of timings at which events are at least sometimes judged as synchronous (Matthews, Welch, Achtman, Fenton, & Fitzgerald, 2016; Yarrow, Jahn, Durant, & Arnold, 2011). The decision boundaries for synchronous or asynchronous judgments differ from the decision boundary for “red first” or “green first” responses. Specifically, in the TOJ model, PSS reflects the differential delay between the two stimuli and the placement of the decision criterion. In the present study, the right and left asynchrony regions of the decision criterion corresponded to participants’ red first or green first responses. While performing the SJ task, participants responded synchronously when sensory evidence for the arrival time difference between red and green targets fell within the synchrony region. Sufficiently asynchronous arrival times of the red preceding the green or the red following the green would generate asynchronous judgments. Therefore, the SJ model provides two decision boundaries which reflect the differential delay and the extent of the two decision criteria (Yarrow et al., 2011). The extents of the two criteria are the distances of a subjective timeline of SOAs, if the difference in central arrival times falls between the criteria extent, the observer calls the stimuli simultaneous.

From this perspective, temporal precision in the SJ model relies on the placement of two decision criteria and can be indexed by the distance between decision boundaries. Yarrow et al. (2011) required participants to first complete an SJ question and then a TOJ question. They described that the low boundary was between judging that the sound preceded the light and that the two stimuli were simultaneous. In contrast, the high boundary was between judging stimuli as simultaneous and judging that the light preceded the sound. In Experiment 3, we combined the SJ and TOJ tasks to create a new indicator of temporal precision, and further investigate the effect of phasic alertness on it.

Method

Participants

A power analysis (Faul et al., 2007) indicated a sample of 12 for adequate power ($1-\beta \geq 0.80$) to detect a large effect ($\eta^2_p = 0.40$). We recruited 33 participants (11 males, age ranging from 18 to 24 years, mean age = 21.3 years) from Southwest University of China. According to the fitting coefficient (R^2) of each block of every participant, 5 participants were excluded for failure to do the task properly ($R^2 < 0.75$). All participants had normal or corrected-to-normal vision, normal hearing, and no neurological or psychiatric antecedents. At the end of experiment, they received payment for their participation.

Stimuli and apparatus

The stimuli and apparatus were the same as in Experiment 1.

Design and procedure

In this dual experiment, participants were first required to decide whether the red and green dot occurred synchronously or asynchronously. If a participant indicated that the dots occurred synchronously, this trial ended. Otherwise, participants had to further judge which dot appeared first in the second question mark. This experimental session consisted of visual and auditory blocks of 336 trials each, with three 1-minute rests within each block and a 2-minute rest between blocks.

Results

The dual SJ and TOJ questions could simultaneously fit the leftmost and rightmost functions (based only on TOJs for trials judged successive) and could offer the low boundary and high boundary components for the cumulative Gaussians of the simultaneity fit (Yarrow et al., 2011). The JND of the dual tasks was determined as the distance between the low and high boundaries. The high boundary was the function of judging red first, and the low boundary was the function of 1-the proportion of judging green first. The PSS fell at the midpoint of the difference of the two cumulative Gaussians, so it would be similar to the PSS commonly obtained when a single Gaussian function is used to fit SJ data. The ratio of responses of judging red first and the proportion of judging green first were calculated for each SOA. MATLAB Statistics and Curve Fitting Tools were used for the statistics calculation and graphic presentation of the results. The ANOVA on PSS revealed no significant effect of cue [$F(1, 27) = 2.826$, $p > 0.05$, $\eta^2_p = 0.095$], and PSS in trials was not affected by warning cue nor by channel [$F(1, 27) = 0.08$, $p > 0.05$, $\eta^2_p = 0.003$]. There was no significant interaction between cue and channel [$F(1, 27) = 0.298$, $p > 0.05$, $\eta^2_p = 0.011$]. The results of JND scores demonstrated a significant main effect of cue condition [$F(1, 27) = 23.486$, $p < 0.001$, $\eta^2_p = 0.465$]. The main effect of channel was not significant [$F(1, 27) = 0.001$, $p > 0.05$, $\eta^2_p = 0.001$], nor was the interaction between cue and channel [$F(1, 27) = 2.01$, $p > 0.05$, $\eta^2_p = 0.069$].

Figure 6 shows the proportion of responses of visual block (Graph a) and auditory block (Graph b) at each SOA fitted with the Gaussian cumulative distribution function. In Graphs a and b, the green lines represent "the proportion of judging green first," and the red lines represent "the proportion of judging red first." We then computed a paired-sample *t* test (one-tailed) of response proportion at every SOA. For responses of judging red first, Bonferroni correction for multiple comparisons showed that there was a significant difference between the visual cue and no cue conditions for SOA = 26 ms, 52 ms, 78 ms ($ps \leq 0.0056$). Under the auditory condition, SOA = −26 ms, 78 ms, 104 ms showed a significant difference between the cue and no cue condition ($ps \leq 0.0056$). For the response ratios of the proportion of judging green first, Bonferroni correction for multiple comparisons showed that there was significant difference between the visual cue and no cue conditions for SOA = −104 ms, ±78 ms, −52 ms, −26 ms ($ps \leq 0.0056$), whereas under the auditory condition, only SOA = −52 ms, 26 ms showed a significant difference between the cue and no cue conditions ($ps \leq 0.0056$). These results imply that the effect on enhanced temporal precision shows at the short and medium SOAs.

Figure 7 shows the results of a paired-sample *t* test (one-tailed) of RTs for the SJ (Graph c). After Bonferroni correction for multiple comparisons of SJ results, there was a significant difference between the visual cue and no-cue conditions at

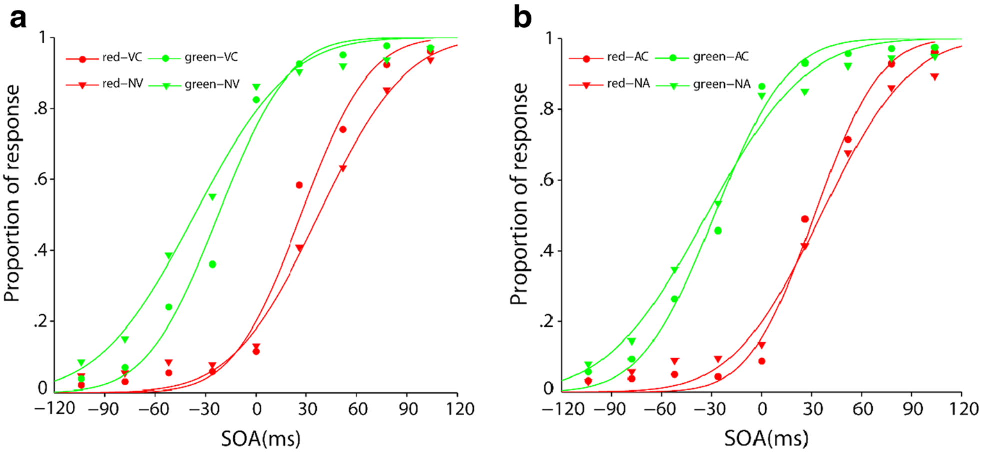

Fig. 6. From the data of the dual task, the proportion of responses of visual (Graph a) and auditory block (Graph b) at each SOA level were fitted with the Gaussian cumulative distribution function. The green lines represent "the proportion of judging green first," and the red lines represent "the proportion of judging red first." *VC* visual cue; *NC* no visual cue; *AC* auditory cue; *NA* no auditory cue. Negative values represent the red dot following the green dot, and the positive represent red dot preceding the green.

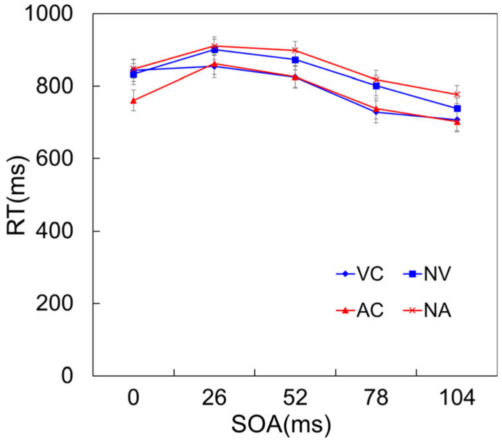

Fig. 7. RTs for the SJ question in the dual task.

SOA = 26 ms, 52 ms, 78 ms, 104 ms ($ps \leq 0.01$). While under the auditory condition, all SOAs showed a significant difference ($ps \leq 0.01$). These results imply that participants benefitted from visual and auditory alerting cues in the first SJ question.

Discussion

In Experiment 3, we employed a dual SJ and TOJ task that asked participants to first judge whether the red and green dots appeared synchronously and then to judge which dot appeared first. Previous research indicated that this pair of judgments could fit simultaneity data and would fit the low and high boundary component cumulative Gaussians of successive trials, which made full use of a ternary division of responses (Yarrow et al., 2011). In contrast to the TOJ and SJ tasks in Experiments 1 and 2, the calculation of JND of the dual task was determined by the two boundaries. This model has the additional advantage of being able to capture a flattened peak due to a broad range of values being perceived as simultaneous. In the present study, the low and high boundary was respectively calculated as the proportion of judging green first and the proportion of judging red first. Our results found that the distance between the low and high boundary was significantly reduced under alerting cues compared with the no-cue condition [visual: JND = 19.22 ms vs. 25.77 ms; and auditory: JND = 17.84 ms vs. 27.29 ms]. Consistent with the preceding performance on the TOJ and SJ tasks, the reduced JNDs in the dual task suggest that phasic alertness could enhance temporal precision. Furthermore, there was no interaction between cue and channel. The PSS of the dual tasks also showed that alerting cues in the visual and auditory modalities did not affect temporal accuracy (PSS). From the analysis of response proportions for the two fitting functions, the results were similar to those of Experiments 1 and 2. That is, participants in the visual and auditory alerting conditions made more precise responses at short and medium SOAs. The analysis of RTs for SJs showed that participants had to judge whether red and green dots appeared synchronously or asynchronously, both visual and auditory alerting cues significantly decreased reaction times.

General discussion

Attention is one important determinant of time perception. Although it is the most basic intensity aspect of attention, the influence of alertness on temporal precision has not yet been fully identified. The present experiments were designed to evaluate the effect of alertness in the visual and auditory modalities on the visual temporal perception. To that end, we chose a salient yellow lightning form and small screechy pure tone as audio-visual warning cues and used the TOJ task in Experiment 1, the SJ task in Experiment 2, and the dual SJ and TOJ tasks in Experiment 3. Although these three tasks follow different paradigms of visual temporal perception, the results of all were associated with improved performance under the alerting condition. By analyzing the PSS and JND from the three experiments, we found that trials with warning cues had significantly smaller JND values compared with trials without warning cues. Our results also revealed that PSS did not differ significantly between cueing conditions. These results indicate that visual and auditory alerting cues prominently sharpen visual temporal precision and did not deflect participants' response accuracy. We will discuss the implications of these results in the following paragraphs.

Several studies have demonstrated that orientation of attention can produce bias toward attended stimuli or position, which would result in a shift of PSS. Particularly when the temporal delay between the onsets of two stimuli is too small to permit accurate order discrimination but observers are forced to guess anyway. The present study manipulated visual and auditory warning cues to precede the targets and focused on the effects of alertness on the whole temporal perception rather than on either of the two targets. Under this condition, warning cue would not shorten any certain target's perceptual latency, so the PSS did not show any significant shift. The reduced RTs and improved response precision that we found were consistent with the results of previous studies (Fecteau & Munoz, 2007; Hackley & Valleinclán, 2003). The reduced JND scores of participants in the three experiments together suggest that phasic alertness can enhance temporal precision of visual perception. That is, observers in the alerting condition needed a shorter time between targets to judge reliably the correct temporal order than in the condition without warning cues. These results are consistent with Chica and Christie (2009), who found evidence that exogenous cues improved performance on temporal precision. Nevertheless, our results are possibly opposite to Yeshurun and Levy's (2003) finding that spatial attention impaired temporal precision. This consequence may be affected by location of spatial cues, which induced enhanced spatial resolution rather than temporal precision in the orienting paradigm.

Generally speaking, warning cues often trigger two processes simultaneously: an immediate increase in automatic arousal and strategic temporal expectancy toward the target (Weinbach & Henik, 2013). Temporal expectancy refers to the ability to anticipate when a forthcoming event will occur by using temporal information. Although they are physiologically distinct mechanism, their effects co-occur often and are entangled with each other (Hackley et al., 2009). Most studies showed that both phasic arousal and temporal preparation could have a beneficial influence on perceptual measures like detection and discrimination accuracy (Lu, Wei, & Cai, 2015; Seibold, Bausenhart, Rolke, & Ulrich, 2011). Although it is impossible to eliminate any of them completely, manipulating the time uncertainty could partially disassociate their effect (Rolke & Hofmann, 2007). Previous studies indicated that a constantly sequential foreperiod (the interval between cue onset and target onset) helped participants form the high temporal expectancy (Bausenhart, Rolke, & Ulrich, 2008). While the variable foreperiod paradigm holds that, the length of the foreperiod varies from trial to trial, participants hardly exploit temporal information with the order of the foreperiod unknown to them (Seifried, Ulrich, Bausenhart, Rolke, & Osman, 2010). Steinborn and Langner (2012) also observed that arousal could modulate temporal preparation under increased time uncertainty. In the present study, our manipulation of a random foreperiod (250~700 ms) between warning cue onset and target onset could largely neutralize the effects of temporal expectancy. Therefore, participants' performance was more associated with phasic arousal rather than strategic mental operations. Liang, Zhang, and Bao (2015) made similar conclusions in a recent study that demonstrated that temporal precision improved under higher arousal induced by emotional pictures.

While engaged in a cognitive task, participants' attention often cycles between task relevant information available in the external environment and that available from internal sources (Smallwood et al., 2004). This attentional shift that accompanies the activities of internally generated information represents external perceptual information, which can be operationalized as task-unrelated thought (Smallwood, Baracaia, Lowe, & Obonsawin, 2003) or zoning out (Schooler, 2002). A closely related phenomenon in psychological research, the notion of attentional lapses (Reason & Lucas, 1984), reflects a situation when "an action is triggered inappropriately… is targeted at the wrong stimulus…or when a plan becomes derailed by distraction" (Manly, Robertson, Galloway, & Hawkins, 1999). As the intensity aspect of attention, alertness is of special importance and requires a person to remain ready to complete the ongoing task. It seems that the alerting effect in the present study may result partially from a reduction in nonspecific lapses, such as motor errors and general inattention. If the visual and auditory alerting cues decreased attentional lapses, one would expect a significantly alerting cue boost at all SOA levels, because motor errors and general inattention do not depend on stimulus subtly. From our three experiments, the results pertaining to response ratios showed that alerting cues steadily benefit the short and medium SOA condition, not all SOAs (see Discussion 1). This differential benefit points to a specific enhancement in temporal precision rather than to a reduction in nonspecific attentional lapses. It should be noted that there is a difference between the visual and auditory cues on the response ratios in the SJ and dual tasks, with visual alerting cues showing better performance than auditory cues, possibly due to the visual temporal perception task. This occurrence differs from the RT results (see Discussion 2), in which auditory alerting improved response speed more greatly than visual cues (Recanzone, 2009; Wada, Kitagawa, & Noguchi, 2003). This differential alerting effect on temporal precision and RTs might be modulated by visual and auditory modalities of task and cues.

For a long time, the consensus was that the effect of alerting cues is limited to late stage in the stimulus-response chain. That is, that phasic alertness produces faster motor execution of responses compared with the no cue condition (Coull & Nobre, 1998; Niemi & Näätänen, 1981). However, in the present study, participants were asked to conduct the temporal order task and successively experienced alerting arousal, target stimuli discerning, response selection, and response stage. Our RTs results on three tasks clearly showed that visual and auditory warning cues can improve participants' execution of responses. Previous event-related potential (ERP) studies have demonstrated an alerting-signal-based shortening of the time interval between stimulus presentation and the onset of the lateralized readiness potential, which indicates that alerting cues facilitate early processing of response selection (Hackley & Valle-Inclán, 2003; Hackley & Valleinclán, 1998, 1999). Conversely, the alerting cues also reduced JNDs compared with the no cue condition. That is, phasic alertness can improve participants' perceptual precision. Kusnir, Chica, Mitsumasu, and Bartolomeo (2011) analyzed the percentage of consciously reported targets and RTs of correctly discriminated responses in a near-threshold visual task. The results showed that phasic alerting tone could enhance participants' targets detection and discriminating speed, which indicated that phasic alerting could improve visual conscious perception. Similar results showed that phasic alertness could strengthen perceptual sensitivity and discrimination (Lu et al., 2015). Therefore, phasic alertness might simultaneously benefit the early perception and late motor execution of responses.

Previous research about temporal order tasks usually supports that selective attention clearly shifts the PSS to a location or stimulus that is specific and meaningful to participants, whereas the JND scores do not change significantly (Spence

& Parise, 2010). We attributed this effect of response or decisional biases to implicit and explicit orientation of attention. On the contrary, the results of our study showed that phasic alertness significantly decreased JND scores and had little influence on PSS. Thus, the difference in JND and PSS in our study and previous studies may reveal two distinct processes underlying temporal perception. We inferred that temporal precision and the perceptual inclination of participants in judging temporal order have their corresponding cognitive mechanism. Future studies should investigate the cognitive mechanisms underlying temporal perception in more depth.

Phasic alertness is defined as stimulus-driven, which indicates that the salient and changing cues preceding targets could increase and maintain preparation for an impending stimulus. Our findings might partially explain the attentional capture effect of single cues and color singletons on visual sensitivity (White, Lunau, & Carrasco, 2014), which is susceptible to a temporary state of participants. A recent study also indicated that phasic auditory alertness can improve visual conscious perception (Kusnir et al., 2011). Another study demonstrated that phasic alertness can modulate executive control by enhancing global processing of visual stimuli (Weinbach & Henik, 2011). Combined with the present experimental results, we can confirm that phasic alertness indeed improves visual temporal perception. However, every coin has two sides, and alertness is no exception. While alertness can help allocate cognitive resources to identify and respond to targets within a very short period of time, this characteristic frequently makes people unconsciously ignore other potentially important elements of their surroundings (Ball & Sekuler, 1981; Stanley & Matthews, 2003).

Conclusions

The present study used TOJ, SJ, and a combination of SJ and TOJ tasks. The results demonstrate that alerting cues in visual and auditory modalities reduced visual JNDs while not changing visual PSS. Decreased RTs and improved response precision at SOAs were found in the alerting cue condition. Our study might shed light on the influence of the basic aspect of attention-alertness on the visual temporal perception.

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