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Abstract

The occurrence of a weak auditory warning stimulus increases the speed of the response to a subsequent visual target stimulus that must be identified. This facilitatory effect has been attributed to the temporal expectancy automatically induced by the warning stimulus. It has not been determined whether this results from a modulation of the stimulus identification process, the response selection process or both. The present study examined these possibilities. A group of 12 young adults performed a reaction time location identification task and another group of 12 young adults performed a reaction time shape identification task. A visual target stimulus was presented 1850 to 2350 ms plus a fixed interval (50, 100, 200, 400, 800, or 1600 ms, depending on the block) after the appearance of a fixation point, on its left or right side, above or below a virtual horizontal line passing through it. In half of the trials, a weak auditory warning stimulus (S1) appeared 50, 100, 200, 400, 800, or 1600 ms (according to the block) before the target stimulus (S2). Twelve trials were run for each condition. The S1 produced a facilitatory effect for the 200, 400, 800, and 1600 ms stimulus onset asynchronies (SOA) in the case of the side stimulus-response (S-R) corresponding condition, and for the 100 and 400 ms SOA in the case of the side S-R non-corresponding condition. Since these two conditions differ mainly by their response selection requirements, it is reasonable to conclude that automatic temporal expectancy influences the response selection process.

Key words: Expectancy; Time course; Priming; Auditory temporal processing; Visual form processing; Reaction time

Introduction

Several studies have demonstrated that the latency of the response to a stimulus in reaction time tasks is reduced by the preceding presentation of another stimulus (for reviews, see Refs. 1,2). This effect has been related to the arousal and the automatic temporal expectancy produced by the warning stimulus. Arousal is considered to be a process that causes an increase in the excitability of brain circuits in general (see Refs. 3,4). It begins immediately and lasts a few hundred milliseconds at most. Automatic temporal expectancy is most commonly treated as a process that induces a time-dependent increase in the excitability of a specific sensorimotor circuit (see Refs. 2,5,6, for a definition of automatic temporal expectancy). Its action manifests at the times when relevant events tend to occur and strongly depends on the relative probability of occurrence of these events at these times. Presumably, arousal contributes only to producing the facilitatory effect of strong warning stimuli. The facilitatory effect of low-intensity warning stimuli is supposed to depend mainly on automatic temporal expectancy (7).

There is evidence that automatic temporal expectancy acts mainly in premotoric processes. For example, it has been demonstrated that the interval between the onset of the stimulus and the onset of the lateralized readiness potential, which indexes sensory processing and sensorimotor coupling, is reduced by a warning stimulus (for a review, see Ref. 8). Behavioral evidence suggesting that automatic temporal expectancy specifically modulates sensory processing has been obtained. Bausenhart et al. (9) investigated the influence of a warning stimulus on the psychological refractory period effect, which is attributed to a competition between processes occurring before response selection. They demonstrated that a visual warning stimulus reduces the interference of a visual discrimination with an

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auditory discrimination performed 50 or 200 ms later. Of importance, the magnitude of this reduction was similar to the shortening of the reaction time to the visual stimuli produced by the warning stimulus. Rolke and Hofmann (10) showed that a visual warning stimulus shortened reaction time and improved accuracy in a discrimination task in which the visual targets were backward masked. Since this procedure selectively influences early sensory processing (11), the results are compatible with the idea that a warning stimulus increases early visual processing efficiency. More direct support for this hypothesis was obtained by Pinheiro and Ribeiro-do-Valle (12). These investigators demonstrated that the detectability of a visual target, as indicated by the d-prime measure, is increased by an auditory warning stimulus presented 200 ms in advance. Behavioral evidence that automatic temporal expectancy also modulates the response selection process is scarcer. Apparently, it has only been reported by Fischer et al. (13), who described a larger facilitatory effect of a 250-ms prior auditory warning stimulus for the side corresponding than the side non-corresponding stimulus-response condition in a visual shape identification task.

Larger effects of automatic temporal expectancy were observed in tasks that require more elaborate premotoric processes, such as identification of target stimuli and response choice. Simon and Slaviero (14), for example, reported a larger visual warning stimulus effect in a reaction time task involving the identification of the color of the target stimulus than in a reaction time task involving only the detection of the target stimulus. A similar result was obtained by Del-Fava and Ribeiro-do-Valle (7). These authors evaluated the reaction time to a visual target in the absence and 200 ms after the occurrence of a weak auditory warning stimulus. Both a simple task and a go/no-go reaction time task were used to test the participants. A robust facilitatory effect of the warning stimulus was observed. More important, this effect was larger in the go/no-go reaction time task than in the simple reaction time task.

In a simple reaction time task, the target stimulus must simply be detected and the response emitted. In a choice or a go/no-go reaction time task, the target stimulus has to be identified and a choice between responding in a certain way or another or between responding and not responding must be made. Thus, one of these two processes or both could be responsible for the increase of the facilitatory effect of the warning stimulus observed in these tasks. Automatic temporal expectancy could facilitate late sensory mechanisms, accelerating stimulus identification, facilitate response selection mechanisms, accelerating the choice of the appropriate response, or facilitate both of these mechanisms, leading to faster stimulus identification and response choice.

The findings of Bausenhart et al. (9) provide some support for the view that the larger effect of temporal expectancy reported by Simon and Slaviero (14) in a choice task and by Del-Fava and Ribeiro-do-Valle (7) in a go/no-go task involves, at least partially, changes at late sensory levels. The involvement of changes at the response selection level should also be considered on the basis of the finding of Fischer et al. (13).

The present study investigated the relative contribution of the requirement of identifying the target stimulus and the requirement of selecting the proper response to the facilitatory effect of an auditory warning stimulus in choice reaction time tasks. A group of volunteers was tested in a task that required responding with one hand to the upper/lower position of peripheral visual stimuli and with the other hand to the lower/upper position of these stimuli, independent of their shape. Another group of volunteers was tested in a task, which required responding with one hand to the circle/ellipse shape of peripheral visual stimuli and with the other hand to the ellipse/circle shape of these stimuli, independent of their location. Somewhat different stimulus identification mechanisms are mobilized in these two tasks (for a review, see Ref. 15). The appearance of a difference between the facilitatory effects of the warning stimuli in these tasks will suggest that temporal expectancy influences late sensory processing in an important way. Somewhat different response selection mechanisms are mobilized in the side corresponding and the side non-corresponding stimulus-response conditions (16). The appearance of a difference between the facilitatory effects in these two conditions suggests that temporal expectancy influences the response selection process in an important way.

Material and Methods

Participants

Ten male and 14 female healthy undergraduate students, 18 to 30 years old (mean ± SD: 22 ± 1), were tested. All had normal or corrected-to-normal vision and normal audition as shown by a visual acuity test performed on each eye and an auditory sensitivity test performed on each ear. None had previous experience with reaction time tasks or were aware of the purpose of the study. Written informed consent was obtained from all participants.

The Research Ethics Committee of the Instituto de Ciências Biomédicas, Universidade de São Paulo, approved this study.

Apparatus

The participants were tested in a dimly illuminated (<0.1 cd/m^2) and sound-attenuated room. Inside this room there was a table with a framework where a 17-inch video monitor and two lateral loudspeakers (30 cm center to center) were mounted. The participants sat down at the table, with their head positioned on a chin-and-front rest. Their eyes were at the level of the center of the screen of the video monitor and 57 cm away from it. Their ears were 88 cm away from the corresponding side loudspeaker. The screen

of the video monitor was dark gray and its luminance was 23.8 cd/m^2. An IBM-compatible computer controlled by a program developed with the MEL2 software (Psychology Software Tools, USA) generated the stimuli and recorded the responses.

Stimuli

The warning stimulus (S1) was a tone emitted by both loudspeakers with a frequency of 300 Hz, an intensity of 57 dB, and lasting 50 ms.

The target stimuli (S2) were a circle (2.4 deg in diameter and a 0.04-deg wide margin) and an ellipse-like figure (two 2.4-deg arcs of a circle 5.0 deg in diameter, with a 0.04-deg wide margin). Both stimuli were white in color, had a luminance of 34 cd/m^2 and lasted 100 ms. They could appear 1.4 deg to the left or right of a central white fixation point and 0.70 deg above or below a virtual horizontal line passing through this fixation point.

Procedure

Each subject participated in two testing sessions on separate days, not more than 7 days apart. Before each session, they received a brief written explanation about the test they were about to perform. A more detailed oral explanation was provided in the testing room after showing the fixation point, the S1, the S2, and the response keys. The participants were instructed to keep their eyes on the fixation point and respond to the S2 by pressing a left or right side key located over the table. The participant was then asked to perform about 10 practice trials.

The purpose of the first testing session was to train the participant to perform the discrimination task. The session consisted of six blocks of 48 trials, each trial beginning with the appearance of the fixation point. The S2 appeared after 1850 to 2350 ms (varying randomly and continuously) plus a fixed interval (50, 100, 200, 400, 800, or 1600 ms, according to the block) (see Figure 1).

Each of the eight conditions (S2 represented by a circle or an "ellipse" x S2 appearing to the left or right of the fixation point x S2 appearing in the upper or lower location) randomly occurred 6 times in each block. Table 1 summarizes the eight conditions.

Twelve participants (10 females) performed a location identification task. Half of them responded with the left hand to the S2, which appeared in the upper location, and with the right hand to the S2, which appeared in the lower location, and the other half, the inverse. The other 12 participants (4 females) performed a shape identification task. Half of
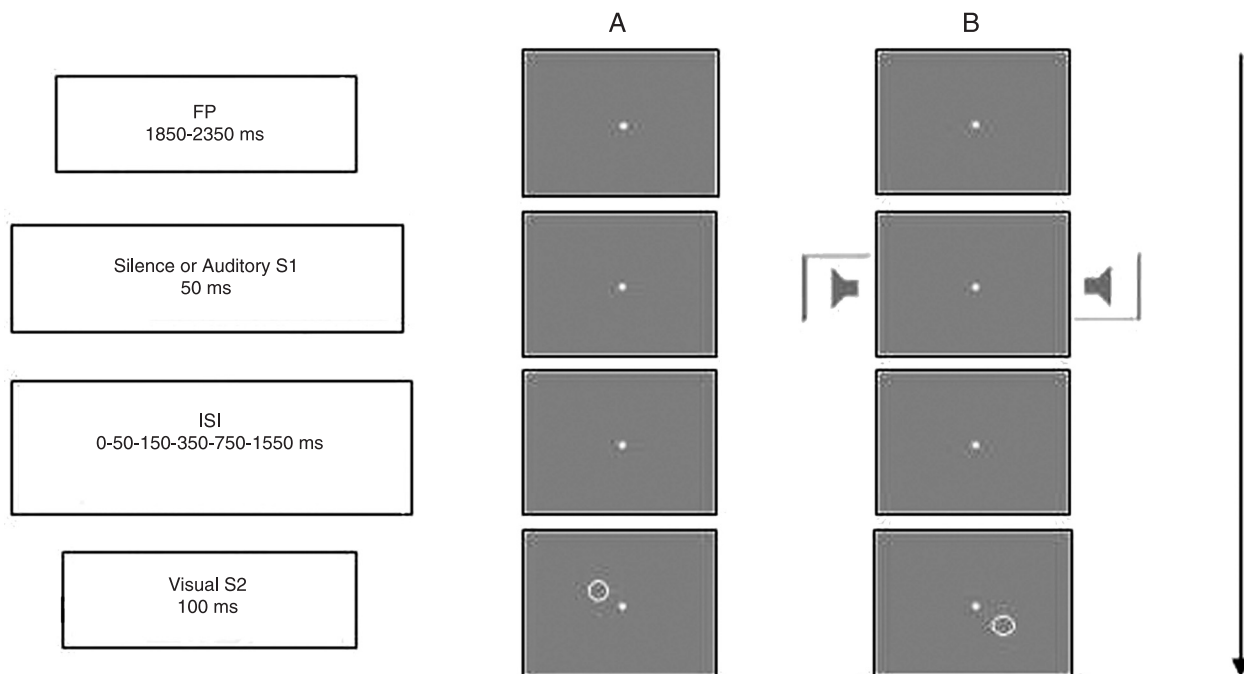

Figure 1. Schematic representation of the sequence of events in a warning stimulus absent trial (Panel A) and a warning stimulus present trial (Panel B). The warning stimulus (S1) was a 300-Hz 57-dB tone, which lasted 50 ms. The target stimuli (S2) were a circle (represented in Panel A) and an ellipse-like figure (represented in Panel B) 34 cd/m^2 bright, which lasted 100 ms. The stimulus onset asynchronies were 50, 100, 200, 400, 800, and 1600 ms (note that these values represent the duration of the S1 plus the duration of the inter-stimulus interval). The message screen, which appears for 400 ms at the end of the trial was not represented. FP = fixation point; ISI = inter-stimulus interval.

them responded with the left hand to the circle and with the right hand to the "ellipse", and the other half, the inverse.

The trial ended with a message lasting 400 ms at the site of fixation. The reaction time in milliseconds appeared when the participant responded between 150 and 1000 ms after the onset of the S2. The message "anticipated" was displayed when he/she responded less than 150 ms after the onset of the S2 and the message "slow" was displayed when he/she responded more than 1000 ms after the onset of the S2. The message "incorrect" was displayed when he/she responded with the wrong hand. The reaction time was presented in blue and error messages in red. Error trials were repeated.

The second testing session consisted of six blocks of 96 trials. In half of these trials only the S2 was presented, as in the first testing session, and in the other half, the S2 was preceded by the S1. Trials with and without S1 occurred randomly. The asynchrony between the onset of the S1 and the onset of the S2 (stimulus onset asynchrony or SOA) was 50, 100, 200, 400, 800, or 1600 ms, depending on the block (by blocking the SOA the time-course of the automatic temporal expectancy influence could be determined adequately). The order of testing these SOA was balanced between the participants of each group and was the same for the two groups. The task to be performed by each participant was the same he/she had trained for. Correct responses were indicated by a blue asterisk and incorrect responses by a red asterisk.

Data analysis

Only the data of the second testing session were analyzed. The median reaction time of each participant was calculated for each condition. In addition, the number of anticipated responses (anticipation error), slow responses (omission errors) and wrong hand responses (inversion errors) of each participant were calculated for each condition.

Reaction time data were submitted to a mixed design analysis of variance (ANOVA) with repeated measures, with the task (location identification or shape identification) as the between-subject factor, and the side stimulus-response (S-R) correspondence (corresponding or non-corresponding), SOA (50, 100, 200, 400, 800, or 1600 ms) and S1 occurrence (absent or present) as the within-subject factors. The data were further analyzed by the *post hoc* Tukey test.

Inversion error data, collapsed across the SOA, were submitted to nonparametric analyses. For each task and for each side S-R correspondence condition, the number of errors in the S1 absent condition was compared to the number of errors in the S1 present condition by means of the Wilcoxon matched pairs test.

The level of significance was set at 0.05 for all analyses and was corrected for multiple comparisons in the case of the inversion error data analyses.

Results

ANOVA did not show any main effect of the task ($F_{1,22}$ =

Table 1. Representation of the eight experimental conditions tested with the group of participants who performed the location identification task and the group of participants who performed the shape identification task.

Task	S2 shape	S2 location	S2 side
Location identification	Circle	Upper	Left
			Right
		Lower	Left
			Right
	Ellipse	Upper	Left
			Right
		Lower	Left
			Right
Shape identification	Circle	Upper	Left
			Right
		Lower	Left
			Right
	Ellipse	Upper	Left
			Right
		Lower	Left
			Right

S2 = target stimulus.

0.06, P = 0.806). It showed an interaction between the task and side S-R correspondence ($F_{1,22}$ = 6.23, P = 0.021) but no other interaction involving the task (Table S1).

The Tukey test demonstrated that reaction time was shorter in the side S-R corresponding condition than in the side S-R non-corresponding condition for both the visual location identification task (P < 0.001) and the visual shape identification task (P = 0.004; Figure 2).

ANOVA also showed a main effect of the side S-R correspondence ($F_{1,22}$ = 65.13, P < 0.001), SOA ($F_{5,110}$ = 5.22, P < 0.001) and S1 occurrence ($F_{1,22}$ = 121.87, P < 0.001) and an interaction between the side S-R correspondence and S1 occurrence ($F_{1,22}$ = 25.84, P < 0.001), the SOA and S1 occurrence ($F_{5,110}$ = 2.60, P = 0.029) and the side S-R correspondence, SOA and S1 occurrence ($F_{5,110}$ = 2.87, P = 0.018; see Table S1).

The Tukey test demonstrated that reaction time was shorter when the S1 was present than when it was absent for the 200-, 400-, 800-, and 1600-ms SOA (in all cases P < 0.001), in the case of the side S-R corresponding condition, and for the 100- and 400-ms SOA (P = 0.041 and P < 0.001, respectively) in the case of the side S-R non-corresponding condition. That is, the warning stimulus produced a facilitatory effect by the four longest SOA in the side S-R corresponding condition but only by the 100- and the 400-ms SOA in the side S-R non-corresponding condition (see Figure 3).

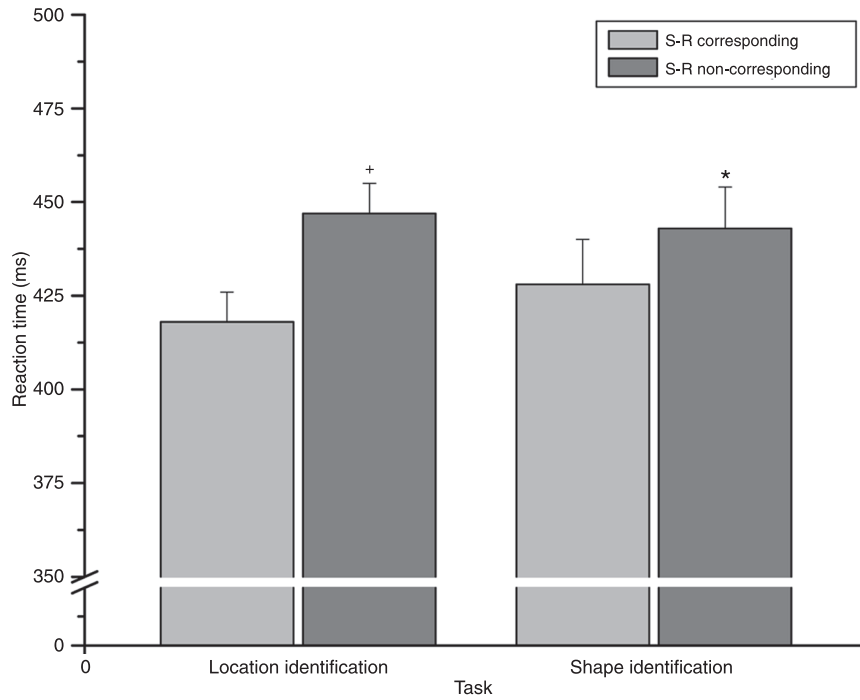The Tukey test also demonstrated that reaction time was

Figure 2. Reaction time in stimulus-response (S-R) side corresponding and non-corresponding conditions for the visual location identification task and the visual shape identification task. Data are reported as means ± SEM for 12 subjects. Data analysis was performed by repeated measures analysis of variance followed by the Tukey test. *P = 0.004; +P < 0.001.
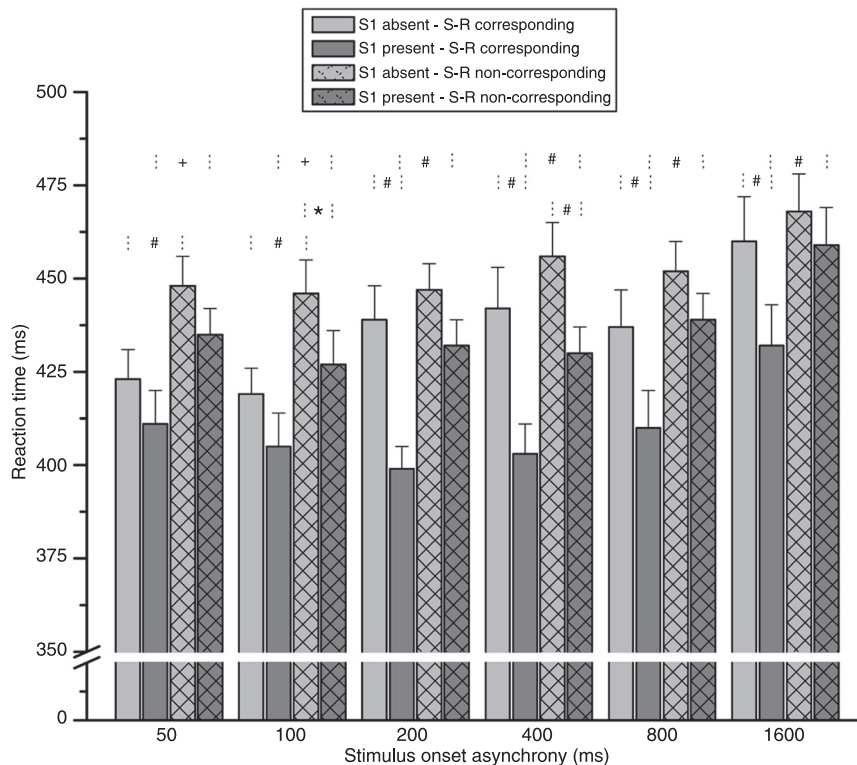

Figure 3. Reaction time in the warning stimulus absent and present trials in the stimulus-response (S-R) side corresponding and non-corresponding conditions across the six stimulus onset asynchronies without separation of the location and the shape identification task data. Data are reported as means ± SEM for 12 subjects. Data analysis was performed by repeated measures analysis of variance followed by the Tukey test. *0.050 > P ≥ 0.010; +0.010 > P ≥ 0.001; #P < 0.001.

shorter when the stimulus and the response were on the same side than on opposite sides for the 50- and 100-ms SOA (P = 0.001 and P < 0.001, respectively) in the case of the S1 absent condition, and for the 50-, 100-, 200-, 400-, 800-, and 1600-ms SOA (P = 0.002, P = 0.004, P < 0.001, P < 0.001, P < 0.001, and P < 0.001, respectively) in the case of the S1 present condition. That is, the side S-R correspondence effect occurred by the two shortest SOA in the S1 absent condition and for all SOA in the S1 present condition (see Figure 3).

The Tukey test further demonstrated that reaction time was longer for the 1600-ms SOA than for the 50-, 100-, 200-, 400-, and 800-ms SOA (P = 0.003, P < 0.001, P = 0.003, P = 0.013, and P = 0.030, respectively).

In the location identification task, anticipation errors occurred in 0.3% of the trials, omission errors in 0.3% of the trials and inversion errors in 4.0% of the trials. In the shape identification task, anticipation errors occurred in 0.3% of the trials, omission errors in 0.3% of the trials and inversion errors in 4.0% of the trials. The Wilcoxon matched pairs test did not show any significant difference between the number of inversion errors in the S1 absent condition and the S1 present condition.

Discussion

The present study demonstrated that a low-intensity open-field auditory warning stimulus produces quite similar facilitatory effects in a visual location identification task and a visual shape identification task. This result precludes any safe conclusion about a modulation of late sensory processing by automatic temporal expectancy. It is equally compatible with an unimportant influence of automatic temporal expectancy on the visual location and the visual shape identification processes and with a similar facilitation of these processes.

The hypothesis that automatic temporal expectancy does not exert any important influence on the identification of the target stimulus feature receives some support from the findings of Ruddell and Hu (17). These investigators demonstrated that the latency of the recognition potential, which is sensitive to late visual processing, is not altered by the presentation of an auditory warning stimulus that causes an important reduction in reaction time to visual stimuli. However, the alternative hypothesis of a similar facilitation by automatic temporal expectancy of the two late visual processes cannot be completely excluded, particularly in view of the findings of Bausenhart et al. (9).

The more robust facilitatory effect of the auditory warning stimulus when the response side coincided with the stimulus side than when it did not for both visual tasks is an important finding of the current study, which confirms and extends the results of Fischer et al. (13). These authors evaluated the effect only for the stimulus onset asynchrony of 250 ms. We did not examine this particular stimulus onset asynchrony, but our results for the 400-ms stimulus onset asynchrony can be considered equivalent to theirs. More original is our observation that in the case of the side stimulus-response corresponding condition the effect occurred when the auditory warning stimulus preceded the visual target stimulus by 200, 400, 800, and 1600 ms and in the side stimulus-response non-corresponding condition the effect occurred only for the 100- and 400-ms stimulus onset asynchronies. These results indicate very clearly that automatic temporal expectancy facilitates more consistently the association of a stimulus and a response, which occur on the same side than the association of a stimulus and a response, which occur on opposite sides.

It has been hypothesized (for a review, see Ref. 18) that the association between a stimulus and a response on the same side would depend on both an indirect sensorimotor route and a direct sensorimotor route. The association between a stimulus and a response on opposite sides would only depend on the indirect sensorimotor route. It is commonly accepted that the indirect sensorimotor route involves the response selection process. The direct sensorimotor route has been supposed not to involve this process. This supposition can, however, be incorrect considering the evidence that this latter route is endogenously modulated (see Ref. 19). A somewhat different hypothesis about the association between a stimulus and a response on the same side or on opposite side was put forward by Hommel and Colzato (20, see also Ref. 16). These authors proposed that this association depends on the formation of a common representation of the stimulus features (including its side) and the response features (including its side). This process would be slower when the stimulus requires a response on the opposite side because there would be a conflict between the spatial code of the stimulus and that of the response. Common to both hypotheses is the assumption that the arbitrary association between a particular stimulus feature and the same side or the opposite side response involves to a certain extent the response selection process.

The relatively low number of inversion errors in all conditions of the current study strongly suggests that the response selection process played a major role in all of these conditions. It is reasonable, then, to suppose that the clear-cut facilitatory effects of our auditory warning stimulus in the side stimulus-response corresponding and non-corresponding conditions in both tasks were due at least partially to an influence of automatic temporal expectancy on the response selection process.

The more consistent facilitation of reaction time by the auditory warning stimulus demonstrated in the side stimulus-response corresponding condition than in the side stimulus-response non-corresponding condition cannot be attributed to a difference in the sensory processes involved in these two conditions. The difference cannot be attributed also to the executive motor processes involved in these two conditions. Considering the belief that the direct sensorimo-

tor route does not involve any response selection process, it is important to note the similar numbers of inversion errors in the auditory warning stimulus absent trials and the auditory warning stimulus present trials for both conditions and both tasks; this finding suggests the lack of any important influence of automatic temporal expectancy on this route. One is left then with the conclusion that the difference between the side stimulus-response corresponding and non-corresponding conditions was due to the different response selection processes involved in the two conditions (coupling stimulus and response spatially matching codes in the former condition and coupling stimulus and response spatially conflicting codes in the latter condition).

Taking into account the present findings, the larger facilitatory effect observed by Simon and Slaviero (14) in a choice reaction time task than in a simple reaction time task should be ascribed to a facilitation of the response selection process by temporal expectancy. The same explanation should hold for the larger facilitatory effect in a go/no-go reaction time task than in a simple reaction time task, which was reported by Del-Fava and Ribeiro-do-Valle (7).

Correa et al. (21) hypothesized that the stimulus-response side correspondence effect (difference between reaction time in the stimulus-response side non-corresponding condition and reaction time in the stimulus-response side corresponding condition) would be related to the mobilization of the dorsal visual pathway ("where" pathway), responsible for localizing visual stimuli, but not to the mobilization of the ventral visual pathway ("what" pathway), responsible for identifying the color and shape of visual stimuli. Our finding that this effect did not differ between the visual location and the visual shape identification tasks, both in the absence of the warning stimulus and in its presence, does not support these authors' idea.

A lengthening of reaction time in the stimulus-response side non-corresponding condition under the influence of controlled temporal expectancy was reported by Correa et al. (21). This effect was attributed by them to an interference caused by the simultaneous facilitation of the same side stimulus-response coupling in this condition. No such result was observed in the current study. We found only a shortening of reaction time in the stimulus-response side corresponding condition. This adds to the evidence presented by Nobre et al. (2), which indicates that automatic temporal expectancy and controlled temporal expectancy are different phenomena.

A limitation of this study and in fact of any exclusively behavioral study is the absence of more direct information about what is really going on in the brain during the tests. The evaluation of cortical activity during the performance of our tasks by electrophysiological and neuroimaging techniques could help confirm the interpretation we gave of the current results.

In conclusion, the results obtained in this study do not allow any safe conclusion about a modulation of late sensory processing by automatic temporal expectation. They do, however, strongly support the hypothesis that automatic temporal expectancy importantly influences the response selection.

Supplementary material

Table S1.

Acknowledgments

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