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Relative contribution of expectancy and immediate arousal to the facilitatory effect of an auditory accessory stimulus

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Abstract

An auditory stimulus speeds up a digital response to a subsequent visual stimulus. This facilitatory effect has been related to the expectancy and the immediate arousal that would be caused by the accessory stimulus. The present study examined the relative contribution of these two influences. In a first and a third experiment a simple reaction time task was used. In a second and fourth experiment a go/no-go reaction time task was used. In each of these experiments, the accessory stimulus preceded the target stimulus by 200 ms for one group of male and female volunteers (G_{Fix}). For another group of similar volunteers (G_{Var}) the accessory stimulus preceded the target stimulus by 200 ms in 25% of the trials, by 1000 ms in 25% of the trials and was not followed by the target stimulus in 50% of the trials (Experiments 1a and 1b) or preceded the target stimulus by 200 ms in 6% of the trials and by 1000 ms in 94% of the trials (Experiments 2a and 2b). There was a facilitatory effect of the accessory stimulus for G_{Fix} in the four experiments. There was also a facilitatory effect of the accessory stimulus at the 200-ms stimulus onset asynchrony for G_{Var} in Experiments 1a and 1b but not in Experiments 2a and 2b. The facilitatory effects observed were larger in the go/no-go task than in the simple task. Taken together, these results suggest that expectancy is much more important than immediate arousal for the improvement of performance caused by an accessory stimulus.

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Introduction

Human volunteers are able to respond with a digital movement to a simple visual stimulus in about 200 to 300 ms. When they have to respond differentially to two simple visual stimuli, latencies increase to about 350 to 450 ms (1). The occurrence of another sensory stimulus (auditory, visual) preceding the target visual stimulus usually shortens reaction time by tens of milliseconds (2-5). The magnitude of this facilitatory effect depends on the modality of the accessory stimulus. In general, auditory stimuli cause larger effects than visual stimuli (3,5,6). The intensity of the accessory stimulus also seems to be important. It was shown that strong auditory stimuli produce a larger facilitatory effect than weak auditory stimuli (4,7,8).

The facilitatory effect of the accessory stimulus is related to a certain extent to the interval between its onset and the onset of the target stimulus. Lansing et al. (2) compared reaction times to a visual stimulus presented between 50 and 1000 ms after an auditory stimulus and found a progressive reduction of reaction time as the interval between the onset of the two stimuli increased. This reduction was already evident when the onset asynchrony was 150 ms and reached a maximum for onset asynchronies between 300 and 400 ms. Also using an accessory auditory stimulus and a visual target stimulus, Davis and Green (3) found a maximum facilitatory effect induced by 200-ms stimulus onset asynchrony. According to Niemi and Näätänen (9), the facilitatory effect of an accessory stimulus may increase with interstimulus interval when this is less than 1 s. For longer interstimulus intervals (e.g., 1-4 s) the facilitatory effect may decrease as time uncertainty increases.

Recently Müller-Gethmann et al. (10) evaluated the time-course of the facilitatory effect of an auditory accessory stimulus and a visual accessory stimulus. Only one stimulus onset asynchrony was tested in each block of trials. For the auditory stimulus, a maximum facilitatory effect was seen for asynchronies of 170, 270 and 470 ms. The effect decreased progressively across asynchronies of 870 and 1670 ms and disappeared with asynchrony of 3270 ms. For the visual stimulus a maximum effect was seen for asynchronies of 270, 470 and 870 ms. The effect decreased at the asynchrony of 1670 and disappeared at the asynchrony of 3270 ms.

Niemi and Näätänen (9) suggested that the reduction of reaction time produced by an accessory stimulus may be due to an expectancy process and an immediate arousal process. Expectancy is most commonly treated as a process that induces a time-dependent increase in the excitability of a specific sensorimotor circuit (see Refs. 11-15). Expectancy may strongly depend on the relative probability of occurrence of events in time. Immediate arousal is considered to be a process that causes an increase in the excitability of brain circuits in general (for a clear definition of arousal, see Refs. 16 and 17), occurring after an accessory stimulus and having a relatively short latency and a relatively short duration. When the accessory stimulus is a sound, it may peak 50 to 300 ms later, decreasing progressively during the next few hundred milliseconds (4,7,18,19).

The present study was conducted to examine the relative contribution of expectancy and immediate arousal, as defined above, to the facilitatory effect of an auditory accessory stimulus. It was hypothesized that expectancy would have a major role in causing this effect and that immediate arousal would be much less important.

The expectancy and the immediate arousal actions of the accessory stimulus were evaluated in four experiments. In Experiments 1a and 1b an attempt was made to individualize immediate arousal by presenting the target stimulus only half of the times after the accessory stimulus, a procedure that should considerably reduce expectancy. In Experiments 2a and 2b, the attempt was to individualize immediate arousal by presenting the target stimulus 1000 ms after the accessory stimulus in most of the trials, a procedure that should delay expectancy. The appearance of a conspicuous short-latency (200-ms) facilitatory effect of the accessory stimulus under conditions in which expectancy was not expected to be acting soon after this stimulus would indicate that immediate arousal plays an important role in behavior control.

The Ethics Committee of the Instituto de Ciências Biomédicas, Universidade de São Paulo approved this study and written informed consent was obtained from all participants.

Experiment 1a

A contribution of expectancy to the facilitatory effect of an accessory stimulus could be examined by presenting this stimulus independently of the target stimulus. In this way the accessory stimulus would have no predictive value. A large reduction of the facilitatory effect of the accessory stimulus would indicate a major contribution of expectancy to this effect. Any remaining short-latency facilitatory effect should be ascribed to immediate arousal.

This experiment compared the effect of an accessory stimulus temporally related to the target stimulus to that of an accessory stimulus not associated with the occurrence of the target stimulus. It was predicted that a large facilitatory effect, consequent to an expectancy action of the accessory stimulus and, possibly, an immediate arousal action of this stimulus, would be observed in the first condition. A small facilitatory effect due to an immediate arousal action of the accessory stimulus, or no facilitatory effect at all would be observed in the second condition.

A simple reaction time task was used to test the volunteers. Since in this task both the target stimulus and the response to it are fixed, the accessory stimulus would be able to exert a strong expectancy action when the occurrence of the target stimulus could be predicted.

Method

Participants. Six male and six female 18- to 21-year-old undergraduate students voluntarily participated in the experiment. All were right handed, as indicated by the Edinburgh Inventory (20), and had normal or corrected-to-normal vision and normal audition, as shown by a visual acuity test and an auditory sensitivity test. None of them had previous experience with reaction time tasks or were aware of the purpose of the study.

Apparatus. The participants were tested in a dimly illuminated (<0.1 cd/m^2) and sound-attenuated room. They sat down at a table with their head positioned on a chin-and-front rest. There was a 17-inch video monitor with a loudspeaker on each side (60 cm center to center) on a framework over the table. The center of the screen of the monitor was at the level of the eyes, 57 cm away from them. The front of each loudspeaker was positioned 88 cm from the participant's ear and on the same side of the head. The background luminance of the screen was less than 0.01 cd/m^2 and the screen had a white fixation point in its center. The participants were instructed to keep their eyes on this fixation point and to respond to a visual stimulus presented at the same position by pressing a key located on the table with their right index finger. This target stimulus could be preceded by a tone presented through both loudspeakers. An IBM-compatible computer controlled by a program developed with the MEL2 software (Psychology Software Tools Inc., Pittsburgh, PA, USA) generated the stimuli and recorded the responses.

Procedure. Each volunteer participated in two testing sessions on separate days (not more than seven days apart). Before each session he/she received a brief explanation. A more detailed explanation was given in the testing room while he/she was performing some example trials. The volunteer was then asked to perform several additional practice trials.

The first testing session, consisting of one block of 32 trials, had the purpose of familiarizing the volunteer with the experimental situation. Each trial began with the appearance of the fixation point. Between 2200 and 3200 ms later, in half of the trials, and between 3000 and 4000 ms later, in the other half of the trials, the target stimulus (S2) appeared, that consisted of a vertical line (0.96 degree long) inside a ring (1.15 degree in diameter and a 0.05-degree wide margin). The S2 was white, had a luminance of 25.8 cd/m^2 and lasted 50 ms. The trial ended with a message lasting 200 ms at the site of fixation. Reaction time in milliseconds appeared when the volunteer responded between 150 and 600 ms after the onset of the S2. The messages "anticipated" and "slow" were displayed, respectively, when he/she responded less than 150 ms after the onset of the S2 and more than 600 ms after the onset of the S2. Error trials were repeated.

The second testing session consisted of two phases. In one phase, that comprised four blocks of 32 trials each, only the S2 was presented, as in the first testing session. This was the no-sound phase (no-sound phase condition). For a first group of six volunteers (G_{Fix}) the S2 occurred in every trial. For a second group of six volunteers (G_{Var}) the S2 occurred in only half of the trials; in the remaining trials nothing else appeared on the screen in addition to the fixation point. The interval between the appearance of the fixation point and the appearance of the S2, from now on called foreperiod, was between 2200 and 3200 ms (FP_{2700} condition) in half of the trials and between 3000 and 4000 ms (FP_{3500} condition) in the other half. These conditions occurred randomly. In the other phase of the session, that consisted of four blocks of 64 trials each, a 1000-Hz 73-dB tone (S1), that lasted 50 ms, occurred in every trial between 2000 and 3000 ms or between 2800 and 3800 ms after the appearance of the fixation point. This was the sound phase (sound phase condition). For G_{Fix}, S1 was always followed by S2; stimulus onset asynchrony was 200 ms. For G_{Var}, S1 was followed by S2 in half of the FP_{2700} trials and half of the FP_{3500} trials; stimulus onset asynchrony was 200 ms in the FP_{2700} trials and 1000 ms in the FP_{3500} trials. In the other half of the trials there was no S2 ("catch" condition). The order of the no-sound and sound phase conditions was counterbalanced across subjects. Differently from what occurred in the first session, only error messages were displayed in this second session. Error trials were repeated.

Data analysis. The median reaction time of each block of trials was calculated for each participant for each condition. The number of anticipated responses, slow responses and undue responses (responses in catch trials) was also calculated also for each participant for each condition. Only the data of the second testing session were considered.

Reaction time data were submitted to a mixed design analysis of variance (ANOVA) with repeated measures, having the group (G_{Fix} and G_{Var}) as between-subject factor and the phase (no-sound and sound) and the foreperiod (FP_{2700} and FP_{3500}) as within-subject factors. When appropriate, the data were further analyzed by the Newman-Keuls test. The level of significance was set at 0.05.

Results and Discussion

Anticipations occurred in 4.6% of the trials, omissions in 1.4% of the target stimulus trials, and "false alarms" in 0.1% of the catch trials.

ANOVA showed a main effect of group ($F_{1,10}$ = 5.18, P = 0.046) and foreperiod ($F_{1,10}$ = 28.02, P < 0.001), and an interaction between the group and foreperiod factors ($F_{1,10}$ = 84.63, P < 0.001), the phase and foreperiod factors ($F_{1,10}$ = 107.80, P < 0.001) and the group, phase and foreperiod factors ($F_{1,10}$ = 49.50, P < 0.001). No main effect of phase ($F_{1,10}$ = 0.75, P = 0.406) or interaction between the group and phase factors ($F_{1,10}$ = 1.22, P = 0.295) was observed. The reaction time of G_{Var} was longer than that of G_{Fix} for both foreperiods and for both phases (P < 0.001 in all cases) (see Figure 1). The reaction time of G_{Fix} was shorter for FP_{3500} than for FP_{2700} in the no-sound phase (P = 0.003) but not statistically different between the two foreperiods in the sound phase (P = 0.623). In the sound phase it was shorter than in the no-sound phase for FP_{2700} (P < 0.001) and for FP_{3500} (P = 0.035). The reaction time of

G_{Var} was not significantly different between the two foreperiods in the no-sound phase (P = 0.551); in the sound phase it was longer for FP_{3500} than for FP_{2700} (P < 0.001). It was shorter in the sound phase than in the no-sound phase for FP_{2700} (P < 0.001) and longer in the sound phase than in the no-sound phase for FP_{3500} (P < 0.001).

The absence of the target stimulus in half the trials for G_{Var} was probably responsible for the longer reaction times of this group as compared to those of G_{Fix} in the two phases of the session. In such a situation it would be less advantageous to develop an intense preparation to detect the stimulus and respond to it.

The shorter reaction time of G_{Fix} in the no-sound phase when the foreperiods were long (3000 to 4000 ms) than when the foreperiods were short (2200 to 3200 ms) indicates that the volunteers learned that when the target stimulus did not occur in the first range of foreperiods it would occur in the second range of foreperiods. This would have led them to increase their preparation during this later time interval. It is surprising that the end of the last trial and/or beginning of the current trial and a relatively broad range of long foreperiods (3000 to 4000 ms) could be used so well as temporal landmarks. The shorter reaction times in the sound phase than in the no-sound phase were expected. The repeated occurrence of a conspicuous sound at a fixed time (200 ms) before the onset of the target stimulus may allow the brain to accurately predict the moment of occurrence of this stimulus and to prepare itself optimally to detect and respond to it. The preparation observed in the no-sound phase of the session should be ascribed to expectancy because of its long latency and the preparation observed in the sound phase of the session could be due to expectancy, immediate arousal or both.

The absence of any difference in reaction time of G_{Var} between the short foreperiod and long foreperiod trials during the no-sound phase of the session can be explained by the 50% chance probability of the target stimulus appearing. As considered above, preparing to detect the target stimulus and respond to it would not be very useful in such a situation. Importantly, reaction time in the short foreperiods and 200-ms stimulus onset asynchrony trials of the sound phase was shorter than reaction times in the short (and long) foreperiod trials of the no-sound phase. In the long foreperiods and 1000-ms stimulus onset asynchrony trials of the sound phase, reaction time was longer than that in both the short foreperiod trials and the long foreperiod trials of the no-sound phase. Immediate arousal could seem to be the more likely cause for the increased responsivity 200 ms after the accessory stimulus. It should be noticed, however, that the magnitude of the effect (34 ± 10 ms) was similar to that exhibited by G_{Fix} (26 ± 19 ms). This suggests that there was a contribution of expectancy to this effect, despite the probability of only 25% of occurrence of the target stimulus at that time interval. The decreased responsivity observed 1000 ms after the accessory stimulus confirms the idea that the accessory stimulus became significant to the volunteers. In this case the accessory stimulus would predict that the target stimulus would most likely not occur anymore. The inhibition of responsivity, instead of simply an absence of facilitation, might be a way of warranting that no inappropriate response would be given.

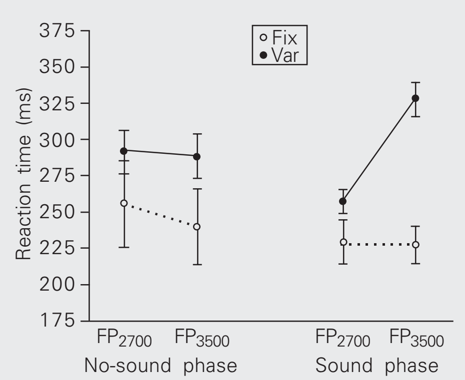

Figure 1. Reaction times of group fix (G_{Fix}) and group var (G_{Var}) in the no-sound and sound phases of the second testing session of Experiment 1a. For G_{Fix} the accessory stimulus always preceded the target stimulus by 200 ms. For G_{Var} the accessory stimulus sometimes preceded the target stimulus by 200 ms and sometimes preceded it by 1000 ms. FP_{2700} and FP_{3500} refer to the interval between the appearance of the fixation point and the appearance of the target stimulus. Data are reported as means ± SEM for 6 volunteers in each group.

Experiment 1b

The predictive value of an accessory stimulus is presumably smaller in a go/no-go reaction time task than in a simple task. When a target stimulus always follows the accessory stimulus in that task, there is no certainty about which exact target stimulus would occur. In the absence of any contingency between the accessory stimulus and the target stimulus, there is no information about whether a target stimulus would occur. It seems reasonable to suppose that in both cases, particularly the latter one, the accessory stimulus would be of very low significance to the volunteers, not causing much expectancy. Its immediate arousal action would then appear in isolation.

Like the previous experiment, this one compared the effect of a temporally informative accessory stimulus to that of a non-informative accessory stimulus. A go/no-go reaction time task, instead of a simple reaction time task, was used to test the volunteers. It was predicted that some facilitatory effect would be observed in the condition of temporal contingency between the accessory and the target stimuli. A much smaller effect was predicted in the condition of no contingency between these stimuli.

Method

Participants. Six additional male and six female students aged 18 to 22 years, with the characteristics described in Experiment 1a, were used.

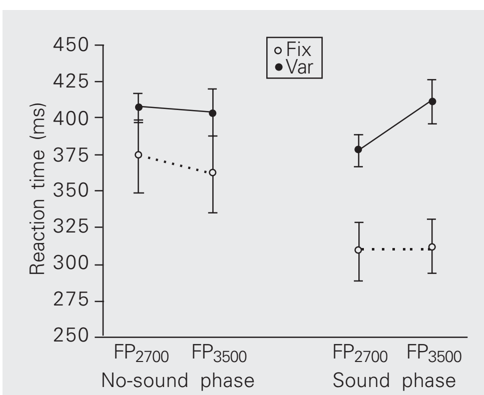

Figure 2. Reaction times of group fix (G_{Fix}) and group var (G_{Var}) in the no-sound and sound phases of the second testing session of Experiment 1b. For G_{Fix} the accessory stimulus always preceded the target stimulus by 200 ms. For G_{Var} the accessory stimulus sometimes preceded the target stimulus by 200 ms and sometimes preceded it by 1000 ms. FP_{2700} and FP_{3500} refer to the interval between the appearance of the fixation point and the appearance of the target stimulus. Data are reported as means ± SEM for 6 volunteers in each group.

Procedure. The volunteers were divided into two groups (G_{Fix} and G_{Var}) that were tested as in Experiment 1a, except that two target stimuli were presented. One target stimulus, called S2+, was identical to the one employed in Experiment 1a. The other target stimulus, called S2-, consisted of a cross (vertical and horizontal arms 0.96 degree long) inside a ring (1.15 degree in diameter and a 0.05-degree wide margin). A response should be given in the presence of S2+ and should be withheld in the presence of S2-. In addition to the messages presented in Experiment 1a, the messages "correct" and "incorrect" were displayed when the volunteer did not respond to S2- and when he/she responded to S2-, respectively.

Data analysis. In addition to reaction time, number of anticipated responses, number of slow responses and number of undue responses were evaluated. Data were analyzed as in Experiment 1a.

Results and Discussion

Anticipations occurred in 0.8% of the trials, omissions in 1.3% of the go trials, and "false alarms" in 1.3% of the no-go trials.

ANOVA showed a main effect of group ($F_{1,10}$ = 5.92, P = 0.035) and phase ($F_{1,10}$ = 22.08, P < 0.001), and an interaction between the group and phase factors ($F_{1,10}$ = 10.45, P = 0.009), the group and foreperiod factors ($F_{1,10}$ = 8.48, P = 0.015) and the phase and foreperiod factors ($F_{1,10}$ = 21.08, P < 0.001). No main effect of foreperiod ($F_{1,10}$ = 2.42, P = 0.151) or interaction between the group, phase and foreperiod factors ($F_{1,10}$ = 3.60, P = 0.087) appeared. Reaction time of G_{Var} was longer than that of G_{Fix} for the two phases (P = 0.013 for the no-sound phase and P < 0.001 for the sound phase), and for the two foreperiods (P < 0.001 in each case) (see Figure 2). The reaction time of G_{Fix} was shorter for the sound phase than for the no-sound phase ($P < 0.001$) and the reaction time of G_{Var} did not differ between the sound phase and the no-sound phase ($P = 0.324$). Reaction time in the sound phase was shorter than in the no-sound phase for the two foreperiods ($P < 0.001$ in each case); reaction times in the no-sound phase did not differ between the two foreperiods ($P = 0.074$) but reaction time in the sound phase for FP_{3500} was longer than that for FP_{2700} in the same phase ($P = 0.001$).

The absence of the target stimulus in half of the trials performed by G_{Var} was probably responsible for the longer reaction times of this group as compared to those of G_{Fix} in the two phases of the session. As discussed in the previous experiment, there would be less advantage in preparing to perform the task in an anticipatory manner in such a condition.

The accessory stimulus facilitated the responsiveness of G_{Fix} as indicated by the shorter reaction times in the sound phase as compared to those in the no-sound phase (a difference of 65 ± 13 ms for the short foreperiods and of 50 ± 10 ms for the long foreperiods).

As in the previous experiment, the accessory stimulus facilitated also the responsivity of G_{Var} at the 200-ms stimulus onset asynchrony. The difference in reaction time between the sound phase and the no-sound phase was 30 ± 9 ms, clearly smaller than the differences observed for G_{Fix}. Here no obvious effect of the accessory stimulus was observed at the 1000-ms stimulus onset asynchrony (the difference between the sound phase and the no-sound phase was -8 ± 12 ms).

The marked facilitation of responsiveness occurring 200 ms after the accessory stimulus for G_{Fix} could be ascribed to both expectancy and immediate arousal. The much smaller facilitation for G_{Var} could be due to an isolated action of immediate arousal. The absence of any inhibitory effect of the accessory stimulus at stimulus onset asynchrony of 1000 ms is in accordance with the idea that this stimulus was not highly significant to the volunteers of this group.

Comparison of the results of this experiment with those of the previous experiment showed a strikingly large difference in the magnitudes of the facilitatory effect of the accessory stimulus at the 200-ms stimulus onset asynchrony for G_{Fix} (65 ± 13 ms here against 26 ± 19 ms there). The direction of this difference was opposite to the one expected. A possible reason for this finding is the room available for performance improvement in a simple and a go/no-go reaction time task. According to Henderson and Dittrich (21), the relevant sensorimotor circuit is supposed to be kept greatly facilitated during the trials in a simple reaction time task. Since there should be a limit to how much facilitation could occur without increasing error rate to an unacceptable level, any additional facilitation of this circuit by the accessory stimulus should be limited (see Ref. 22). In a go/no-go reaction time task the relevant sensorimotor circuits would not be kept so much facilitated (see Ref. 21). Then a greater facilitation could be produced by the accessory stimulus before it started to cause too many errors.

For G_{Var} the magnitudes of this facilitatory effect were about the same in this experiment and the previous one (30 ± 9 ms against 34 ± 10 ms). According to the above reasoning, a greater facilitatory effect should also have occurred for this group in the present experiment. Possibly the difference seen between the G_{Fix} was related not only to the available room for performance improvement but also to the higher level of expectancy presumably developed by these groups.

Experiment 2a

The results of the first two experiments suggested an important contribution of immediate arousal to the facilitatory effect of the accessory stimulus. Given the unexpectedness of this finding, it seemed important to confirm it using an experimental procedure different from the one used in those experiments.

An immediate arousal action of the accessory stimulus could be temporally dissociated from the expectancy action of this stimulus. By presenting the target stimulus at a relatively long stimulus onset asynchrony in the great majority of the trials, the facilitatory effect of expectancy would be delayed. An immediate arousal action would presumably continue to occur in the first few hundred milliseconds after the accessory stimulus. Any short-latency facilitatory effect exhibited by the volunteers would have to be credited to it.

In the present experiment a very rare 200-ms stimulus onset asynchrony was mixed with a very frequent 1000-ms stimulus onset asynchrony in the same block of trials. It was predicted that a large facilitatory effect would occur with the long time interval. A very small or no facilitatory effect was predicted for the short time interval. As in Experiment 1a, a simple reaction time was used to test the volunteers.

Method

Participants. Ten additional male and ten female 18- to 25-year-old students, with the characteristics described in Experiment 1a, were used.

Procedure. The volunteers were tested as in Experiment 1a in two sessions.

The first testing session consisted of one block of 34 trials. Each trial began with the appearance of the fixation point. Some time later appeared the target stimulus (S2), that consisted of the vertical line inside the ring. The latency for the appearance of the S2 ranged between 2200 and 3200 ms (FP_{2700} condition) in the 17th and 34th trials and between 3000 and 4000 ms (FP_{3500} condition) in the remaining trials. The trial ended with the message indicating the performance of the volunteer. Error trials were repeated.

The second testing session had two phases. One phase consisted of four blocks of 34 trials. These trials were as in the first testing session. This was the no-sound phase (no-sound phase condition). The other phase of the session consisted of four blocks of 68 trials. The latency for the appearance of the S2 ranged between 2200 and 3200 ms in the 17th, 34th, 51st and 68th trials and between 3000 and 4000 ms in the remaining trials. The tone (S1) described in Experiment 1a was presented before the S2. For a group of 10 volunteers (G_{Fix}), stimulus onset asynchrony was always 200 ms. For another group of volunteers (G_{Var}), stimulus onset asynchrony was 200 ms in the 17th, 34th, 51st and 68th trials and 1000 ms in the remaining trials. This was the sound phase (sound phase condition). The appropriate message was presented at the end of the error trials. These trials were repeated.

Data analysis. Data were evaluated and analyzed statistically as in Experiment 1a.

Results and Discussion

Anticipations occurred in 3.5% of the trials and omissions in less than 0.1% of the trials.

ANOVA showed a main effect of foreperiod ($F_{1,18}$ = 209.01, P < 0.001), and an interaction between the group and phase factors ($F_{1,18}$ = 6.43, P = 0.021), the group and foreperiod factors ($F_{1,18}$ = 57.10, P < 0.001) and the group, phase and foreperiod factors ($F_{1,18}$ = 40.12, P < 0.001). No main effects of group ($F_{1,18}$ = 3.20, P = 0.091) and phase ($F_{1,18}$ = 1.97, P = 0.177) or interaction between the phase and foreperiod factors ($F_{1,18}$ = 0.31, P = 0.583) were observed. The reaction time of G_{Fix} was shorter for FP_{3500} than for FP_{2700} in the no-sound phase (P < 0.001) but not statistically different between the two foreperiods in the sound phase (P = 0.346) (see Figure 3). It was shorter in the sound phase than in the no-sound phase for FP_{2700} (P < 0.001) but not statistically different between the two phases for FP_{3500} (P = 0.375). The reaction time of G_{Var} was shorter for FP_{3500} than for FP_{2700} in the two phases ($P < 0.001$ in each case). It was longer in the sound phase than in the no-sound phase for FP_{2700} ($P < 0.001$) but not statistically different between the two phases for FP_{3500} (P = 0.109).

The shorter reaction times of the two groups in the long foreperiod (3000 to 4000 ms) trials than in the short foreperiod (2200 to 3200 ms) trials of the no-sound phase indicate that the volunteers developed a preparation to respond to the target stimulus in the much more frequent foreperiods. No further reduction of the reaction times of G_{Fix} was seen when the accessory stimulus was presented 200 ms before the target stimulus in the sound phase. These results extend the ones of Experiment 1a by showing that preparatory processes can develop both in the absence of a conspicuous accessory stimulus and a very frequent large range of long foreperiods and in the presence of such a stimulus and only one short stimulus onset asynchrony. The similarity of the reaction times of G_{Fix} in the sound phase to that in the long foreperiod trials of the no-sound phase suggests that the only action exerted by the accessory stimulus was an expectancy one. The increased reaction time of G_{Var} in the rare short foreperiods and 200-ms stimulus onset asynchrony trials of the sound phase as compared to the reaction times in both the short and the long foreperiod trials of the no-sound phase could be explained by an inhibition of responsiveness by the accessory stimulus. In this way premature responses would be avoided. The result argues against a significant immediate arousal action of the accessory stimulus. The similar reaction time of G_{Var} in the frequent long foreperiod trials of the no-sound and that in the long foreperiods and 1000-ms stimulus onset asynchrony trials of the sound phase demonstrate once more the high competence of the organism to use any available temporal information in the environment to prepare to perform the task in the most efficient way.

It is interesting to compare the results obtained with G_{Var} here with those obtained with the same group in Experiment 1a. In both cases an inhibitory effect of the accessory stimulus was observed in the trials where the target stimulus had a low probability of occurring, namely, the long foreperiods and 1000-ms stimulus onset asynchrony trials in that experiment and the short foreperiods and 200-ms stimulus onset asynchrony trials here. A negative expectancy generated by the accessory stimulus could explain these effects.

Experiment 2b

It could be argued that a facilitation of responsiveness by immediate arousal was not demonstrable in the last experiment for G_{Var} because of the large inhibition of responsiveness produced by expectancy 200 ms after the accessory stimulus. If this were the case, the immediate arousal facilitation should appear in a go/no-go task where expectancy seems not to exert such an inhibitory action.

This possibility was examined in this last experiment. Conditions were the same as in the previous experiment, but the go/no-go task was used to test the volunteers.

Method

Participants. Ten additional male and ten female 18- to 21-year-old students, with the

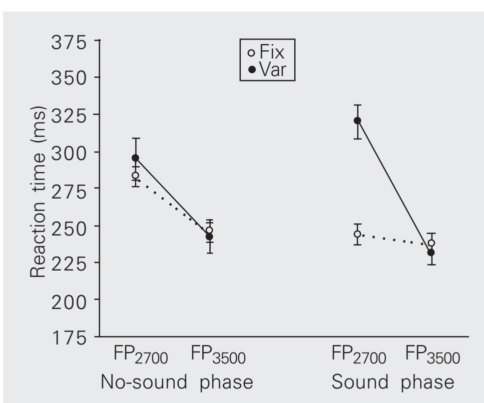

Figure 3. Reaction times of group fix (G_{Fix}) and group var (G_{Var}) in the no-sound and sound phases of the second testing session of Experiment 2a. For G_{Fix} the accessory stimulus always preceded the target stimulus by 200 ms. For G_{Var} the accessory stimulus sometimes preceded the target stimulus by 200 ms and sometimes preceded it by 1000 ms. FP_{2700} and FP_{3500} refer to the interval between the appearance of the fixation point and the appearance of the target stimulus. Data are reported as means ± SEM for 10 volunteers in each group.

characteristics described in Experiment 1a, were used.

Procedure. The volunteers were divided into two groups (G_{Fix} and G_{Var}) that were tested as in Experiment 2a, except that there were two target stimuli. One target stimulus, the S2+, was identical to the one employed in that experiment. The other target stimulus, the S2-, was the cross inside the ring. A response should be given in the presence of the S2+ and should be withheld in the presence of the S2-. In addition to the messages presented in Experiment 2a, the messages "correct" and "incorrect" were displayed when the volunteers did not respond to the S2- and when they responded to the S2-, respectively.

Data analysis. In addition to reaction time, number of anticipated responses, number of slow responses, and number of undue responses were evaluated. Data were analyzed as in Experiment 1a.

Results and Discussion

Anticipations occurred in 0.8% of the trials, omissions in 0.7% of the go trials, and "false alarms" in 2.7% of the no-go trials.

The first ANOVA showed a main effect of phase ($F_{1,18}$ = 44.36, P < 0.001) and foreperiod ($F_{1,18}$ = 41.69, P < 0.001), and an interaction between the group and phase factors ($F_{1,18}$ = 9.87, P = 0.006), the group and foreperiod factors ($F_{1,18}$ = 22.00, P < 0.001) and the group, phase and foreperiod factors ($F_{1,18}$ = 8.90, P = 0.008). No main effect of group ($F_{1,18}$ = 0.03, P = 0.868) or interaction between the phase and foreperiod factors ($F_{1,18}$ = 0.70, P = 0.414) appeared. Reaction time of G_{Fix} was shorter for FP_{3500} than for FP_{2700} in the no-sound phase (P = 0.031) but not statistically different between the two foreperiods in the sound phase (P = 0.464) (see Figure 4). It was shorter in the sound phase than in the no-sound phase for FP_{2700} (P < 0.001) and FP_{3500} (P < 0.001). Reaction time of G_{Var} was shorter for FP_{3500} than for FP_{2700} in the two phases (P < 0.001 in each case). It was not statistically different between the two phases for FP_{2700} (P = 0.087) but was shorter in the sound phase than in the no-sound phase for FP_{3500} (P = 0.005).

As discussed in the previous experiment, the shorter reaction times of the two groups in the long foreperiod (3000 to 4000 ms) trials than in the short foreperiod (2200- to 3200-ms) trials of the no-sound phase indicate that the volunteers developed a better preparation to respond to the target stimulus in those foreperiods. Here, however, this preparation was only partial. An appreciable additional reduction of reaction time in both foreperiod trials occurred for G_{Fix} during the sound phase. A higher cost of preparing to perform the task in a go/no-go task would lead to a high facilitation of responsiveness only when temporal information was more precise. The reaction time of G_{Var} in the short foreperiod and 200-ms stimulus onset asynchrony trials did not differ from that in the short foreperiod trials of the no-sound phase. This result does not support the idea that the accessory stimulus produced an immediate arousal. The shorter reaction time of G_{Var} in the long foreperiod and 1000-ms stimulus onset asynchrony trials as compared to that in the long foreperiod trials of the no-sound phase may be due to the high expectancy generated by the precise temporal information provided by the accessory stimulus.

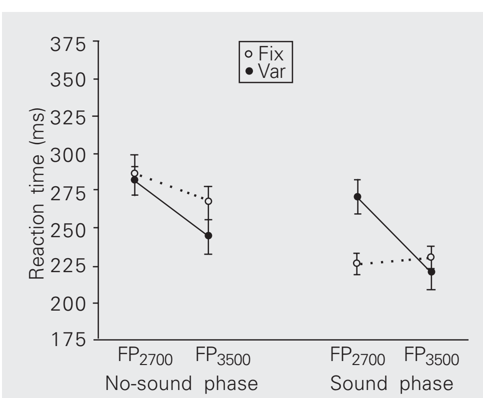

Figure 4. Reaction times of group fix (G_{Fix}) and group var (G_{Var}) in the no-sound and sound phases of the second testing session of Experiment 2b. For G_{Fix} the accessory stimulus always preceded the target stimulus by 200 ms. For G_{Var} the accessory stimulus sometimes preceded the target stimulus by 200 ms and sometimes preceded it by 1000 ms. FP_{2700} and FP_{3500} refer to the interval between the appearance of the fixation point and the appearance of the target stimulus. Data are reported as means ± SEM for 10 volunteers in each group.

General Discussion

The present study demonstrated that an auditory accessory stimulus can increase or decrease responsiveness to a visual target stimulus. In a simple reaction time task, a facilitatory effect was observed under the following conditions: 1) when the target stimulus occurred 200 ms later with a probability of 100%, 2) when the target stimulus occurred 200 ms later with a probability of 25%, and there was a 25% probability of it occurring 1000 ms later and a 50% probability of it not occurring, and 3) when the target stimulus occurred 1000 ms later for series of 15 trials, that alternated with a trial in which it occurred 200 ms later. An inhibitory effect was observed under the following conditions: 1) when the target stimulus occurred 1000 ms later with a probability of 25%, and there was a 25% probability of it occurring 200 ms later and a 50% probability of it not occurring, and 2) when the target stimulus occurred 200 ms later in the 16th trial, after having occurred 1000 ms later for the preceding 15 trials. In a go/no-go reaction time task, a facilitatory effect was observed under the same conditions as reported above for the simple reaction time task. However, this facilitatory effect tended to be larger. No inhibitory effect was observed. Overall, these results suggest that the influence exerted by the accessory stimulus depends very much on the probability of occurrence of the target stimulus and/or of responding a certain time later. The accessory stimulus would lead to a facilitation of the task relevant sensorimotor circuit at the time when it most likely would enter into action and to an inhibition of this same circuit at the time when it would be less likely to enter into action. This is certainly highly adaptive.

A strong dependence of the facilitatory influence of the accessory stimulus on the probability of the target stimulus occurring at a later time has also been reported by several other investigators. The finding was related in part to the expectancy generated by the accessory stimulus (see 9). In a recent study, Coull et al. (23) considered expectancy about when an event will occur to be analogous to the expectancy about where the event will occur, an orienting of attention in time. They demonstrated that expectancy involves an extensive bilateral frontoparietal network, including inferior prefrontal and premotor areas and the left inferior parietal cortex, that would mediate motor preparation.

All the effects of the accessory stimulus observed in the present study can be explained by the action of an expectancy process. This could have caused the facilitatory effects observed, by increasing the excitability of the relevant sensorimotor circuit at the most likely time of occurrence of the target stimulus and corresponding motor response. Its specificity would warrant that the target stimulus (presumably mainly the go stimulus in Experiments 1b and 2b) would be preferentially analyzed and the appropriate response (presumably mainly the go response in the same experiments) given priority over others. As already discussed, the similar early facilitatory effects exhibited by G_{Fix} and G_{Var} in Experiment 1a can most parsimoniously be explained by at least some action of expectancy. In the same way, the larger facilitatory effects exhibited by the volunteers of the two G_{Fix} in the go/no-go task as compared to those in the simple task could be understood in terms of an action of expectancy on a basally weakly facilitated sensorimotor circuit. The late facilitatory effect exhibited by the volunteers of G_{Var} in Experiment 2b was most likely caused by expectancy.

The inhibitory effects of the accessory stimulus that appeared in Experiments 1a and 2a are consistent with a negative action of expectancy. If one accepts the suggestion by Coull et al. (23) that expectancy is an attentional process, in the case directed towards temporal aspects of the envirnoment, it can be imagined that it would cause an inhibition of the task relevant sensorimotor circuit for other time moments than the focused one, in the same way that attention to a certain spatial region causes an inhibition of responding to stimuli in other spatial regions (see Ref. 24). There is no report in the literature of an inhibitory action of the accessory stimulus on responsiveness related to the probability of occurrence of the subsequent target stimulus. Such an action might have gone unnoticed because control conditions without the accessory stimulus, that could serve as reference, were not employed.

An expectancy process could explain not only all the results obtained in the sound phase of the second testing session but also those of the no-sound phase of this session in Experiments 1a, 2a and 2b, as already discussed. The facilitation of responsiveness by events occurring at the end of an immediately preceding trial (such as the emitted response or the response-related message on the screen) or by events occurring at the very beginning of the current trial (such as the appearance of the fixation point) has not been emphasized in the literature. Even when this is clearly shown by the data, as for example in the study of Fernandez-Duque and Posner (5; Experiment 2), it is not discussed. This very robust observation demonstrates how strong is the tendency of the brain to use whichever cue is present in the environment to prepare its future activity.

Immediate arousal apparently did not contribute to any appreciable extent to the early facilitatory effects of the accessory stimulus observed here. Although the early facilitatory effects of the accessory stimulus in Experiment 1a could be explained exclusively by this process, those in Experiment 1b could hardly be explained entirely by it. In addition, the magnitude of the early facilitatory effects exhibited by the volunteers of G_{Fix} in Experiment 2a does not suggest that the accessory stimulus was exerting any other action besides the expectancy one, and the absence of any early facilitatory effect for the volunteers of G_{Var} in Experiment 2b indicates that no immediate arousal action was exerted by the accessory stimulus.

Since it was first proposed by Bertelson and Tisseyre (18), the immediate arousal construct has been used many times to explain the increase in motor response speed (and force) in reaction time tasks caused by an accessory stimulus. Immediate arousal would be stronger for auditory accessory stimuli than for visual accessory stimuli and its level would increase with the intensity of the accessory stimulus (7,25,26). It would be expected to occur for auditory accessory stimuli above 70 dB (see Ref. 7). The results of Experiments 2a and 2b clearly suggest that an automatic, short-latency increase in brain excitability does not necessarily follow the occurrence of such stimuli. Brain excitability is clearly much more dependent on the probability of occurrence of the target stimulus along the trial. Very likely results attributed by authors to an immediate arousal action of the accessory stimulus would be more appropriately explained by a time- and probability-related mechanism, that is, expectancy. The very fact that considerable facilitatory effects can still be observed several hundred milliseconds after the offset of the accessory stimulus (5,7,25) by itself casts doubt about an immediate arousal explanation for them. Also somewhat contradicting this hypothesis is the observation that visual accessory stimuli of the commonly used intensity, considered to be not very effective in causing alertness (see Ref. 25), and 52 dB auditory accessory stimuli, considered to be below the critical intensity level to induce immediate arousal (see Ref. 7), produce an appreciable long-lasting facilitatory effect (5). More devastating for the hypothesis is the electrophysiological evidence presented by Hackley and Valle-Inclán (27) and Müller-Gethmann et al. (10) that sensory and/or sensorimotor processes but not motor processes are facilitated during the first few hundred milliseconds after the accessory stimulus. This indicates that early neural changes are not so generalized as the immediate arousal hypothesis would imply. One wonders whether for most individuals, in the usual experimental environments, arousal level is tonically maintained well above basal levels, impairing any further increase by the accessory stimulus.

It could be questioned whether the facilitatory effects observed in the present study, although not produced by an automatic short-latency process like immediate arousal, may be related to some kind of time- and probability-related arousal or alertness. The assumption that an accessory stimulus can induce such a process is apparent in several more recently published reports (5,28). The hypothesis does not seem to be parsimonious since it assumes that the organism develops a temporally specific preparation for responding but a nonspecific sensorimotor preparation for responding. In contrast with the expectancy mechanism, such a mechanism would be too crude, in adaptive terms, in the commonly employed experimental conditions. There are also suggestions that it would not be possible to maintain more than one sensory or motor neural representation facilitated at the same time (see Ref. 29, for sensory processing, and Ref. 30, for motor processing; see also Ref. 21). It should be noted that attempts to demonstrate physiological changes corresponding to a phasic increase in arousal after an accessory stimulus have not been successful (e.g., Ref. 15).

Expectancy but not immediate arousal (or, possibly, any other kind of arousal) may be responsible for the early facilitatory effect (and inhibitory effect) of a medium intensity auditory accessory stimulus. The tendency of some research groups to attribute the facilitatory effect of a medium intensity accessory stimulus to arousal/alertness, understood as a general increase in the excitability of brain circuits (see Refs. 16 and 17), should be reconsidered.

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