Effect of Adaptation on Auditory Localization and Lateralization

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Summary

This paper presents a series of experiments on the effect of adaptation in localization and lateralization. Localization measurements were performed, in an anechoic room, on the perceived azimuth of a brief 4-kHz tone, coming from the side of a listener, in the presence of a tone at the same frequency and level coming from the front. The frontal source was turned on first, and left on long enough to induce auditory adaptation at that frequency. It was found that, as the duration of this adaptation period increased, the perceived azimuth of the delayed lateral sound shifted towards the side, away from the actual position of its source. Lateralization measurements, using a diotic inducer and a dichotic test signal, confirmed this finding. A study of the time scale of this adaptation effect shows that it can take between 1 s and 10 s to become settled; but the recovery from adaptation is fairly quick, less than 1 s in the case of our experimental conditions.

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1. Introduction

In two recent papers [1, 2] we reported on an effect of auditory adaptation in localization tasks. The main result of our experiments [1] was that a sustained sound, coming from one direction in the horizontal plane, could influence the perceived azimuth of a brief delayed sound coming from a different direction. The same type of effect can be demonstrated under earphones [2]: exposure to a sustained diotic sound can influence the lateralization (apparent locus between the ears) of a delayed dichotic tone.

In those experiments, the pre-exposure to the sustained sound was meant to induce some kind of adaptation. Let us recall that adaptation is a progressive decrease in the response of the sensory system, as a function of time, to a stimulus whose physical characteristics are maintained at a constant. We know fairly well the effect of adaptation on the loudness of a continuous tone, and the conditions where it occurs [3, 4]. Recently, a series of studies were also conducted on the effect of adaptation on the detection of a short increment in a sustained pedestal [5, 6, 7]. It was found that the detection performance of a listener improves as the onset time difference between pedestal and increment is increased, over a period of several seconds. On the other hand, the influence of adaptation on space perception is still not very well known. A review of the relevant literature will be given below.

In the case of our localization experiments, the typical setting and results were as follows. The subject was seated in the centre of an anechoic room, facing two loudspeakers; one of them was right in front of him (azimuth of 0°) and the second one at an azimuth of 15° to the right. The frontal speaker was turned on first, to radiate a continuous pure tone at a constant level. After a certain amount of time, the lateral speaker would send a short tone at the same frequency and level, and the task of the subject was to report the apparent azimuth of the auditory event resulting from the combined action of the two speakers. As the time interval between the onsets of the two sounds was increased, a progressive shift towards the side in the perceived azimuth of the auditory event was observed, away from the frontal region. Most of the measurements were made at 4 kHz, where the effect was found to be the greatest, but the same trend was found at other frequencies, above 2 kHz, or with bands of noise.

As we were running the preliminary experiment, it immediately appeared that the results were very strongly dependent on the position of the listener relative to the sound sources. This comes from the fact that the acoustic field created around the subject by two 4-kHz tones depends on the phase relationship between the two tones. Then the resulting pattern of interference varies with this phase difference. As a consequence, the interaural level difference at the subject's ears is modified accordingly. In other words, when both sources are sounded simultaneously, the apparent azimuth of the resulting sound changes with the acoustic phase difference. One of the aims of the present study was thoroughly to investigate this effect of the ongoing phase difference between the sounds on the strength of the adaptation.

In this paper, we present the results of three main experiments. The first one is concerned with free-field localization, and therefore it is an extension of what was already published [1, 2], with an emphasis on the effect of the phase difference between the sounds. The second experiment was undertaken to study the same effect under earphones, in which we measured the lateralization of a dichotic brief sound in the presence of a continuous diotic sound, as a function of the time difference between their onsets. In this case, these two sounds (central and lateral)

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were chosen so as best to simulate the free-field conditions. Finally, we present the data of a preliminary experiment on the time dependence of the adaptation effect.

2. Survey of previous research

The effects of adaptation on localization have been studied on some occasions in the past. One of the first work on that topic is due to Flugel [8]. He was interested in the lateralization of a diotic tone after exposure to a monaural pure-tone. He found that the pre-exposure to the monaural signal yielded a shift in the lateralization of the diotic tone away from the adapted ear. Flugel thought that the ear was fatigued by the monaural signal, so that its loudness was reduced on that ear, and the diotic test signal was then lateralized towards the other side. A few years later, many papers were published on the same question ([9], [10] and [11]). These authors did not agree with Flugel's assumption. They found that, if the adapting sound is lateralized to one ear using an interaural time difference (instead of an interaural intensity difference), the same effect can be observed. Thurlow and Jack [12], confirmed this result. So, at least, fatigue cannot be the only cause for the shift in lateralization.

Thurlow and Marten [13] suggested that neural adaptation could be responsible for this phenomenon. In his 1973 paper, Thurlow [12] speaks about "adaptation effect in a class of neural elements of the localization system which respond to transient stimuli".

This directional adaptation is also linked to loudness, namely induced loudness adaptation ([14] and [15]). Botte and her colleagues [15] showed that the position inside the head of a monaural pure tone (inducer, on the left ear), presented with a certain delay ΔT after the onset of a continuous tone (on the right ear) was moved toward the left (non-adapted) ear as ΔT increased. The two sounds were at the same level so, with no onset time difference, the image was heard somewhere in the centre of the head. They showed that, while the position of the inducer was moving (with increasing ΔT), the loudness of the continuous tone was reduced, although it stayed constant without inducer.

Adaptation was found to be greater when the signal frequencies (adapter and adapted) were closer ([15] and [16]); Botte et al. [15] and Canévet and Meunier [1] showed that the effect was stronger for high frequency tones.

In all of the studies presented above, the adapting sound was dichotic, so as to induce more adaptation in one ear than in the other. However, the results of Thurlow and Marten [13] and Weerts and Thurlow [17] show that it is not necessary for an adapting sound to be dichotic to induce a shift in the position of a shorter signal. They found, in a free field, a shift in the azimuth of a short signal coming from one side of the subject after an exposure to a longer sound coming from straight ahead. Thurlow and Marten [13] also found more adaptation when the adapter and the adapted tones were close in frequency.

In localization, not only is the apparent position of a sound source modified, but also the differential threshold for localization in the frontal direction is reduced after adaptation to a frontal stimulus ([18] and [19]).

The time dependence of this adaptation is not very well established. The adaptation increases as a function of the duration of pre-exposure, and reaches an asymptote after a certain time. From the results published by Bertrand [20], this duration can be estimated at one minute, but it differs very much among subjects. For example, Moss [21] could not measure this time constant for one subject because the adaptation was complete before the first centering, 5 s after the adapter onset.

Adaptation grows very rapidly at the beginning of the exposure. For example, an effect was observed by Elliott [14] after only 150 ms of exposure. Wakefield [16] studied the effect of the duration of a dichotic interferer on the lateralization of a diotic target (both signals were narrow bands of noise). He found a shift of the target position (measured with an acoustic pointer) for onset delays of only a few milliseconds, an asymptote being reached after 50 ms.

Like the course of adaptation, that of recovery is not well established either. Elliott [14] reported, for a majority of the subjects, a recovery time as long as 10 s, whether the adapting duration was 150, 300 or 1000 ms. On the other hand, Wakefield [16] found a recovery time as short as 250 ms for an adapting sound of 250 ms. The main difference in these two experiments is the type of signals. Elliott used a 500 Hz pure tone for both adapter and adapted signals, whereas Wakefield's signals were narrow bands of noise centred at 6.4 kHz.

3. Localization experiment

The experimental arrangement was fully described in [1]. We shall simply recall the procedure, with an emphasis on the physical characteristics of the signals.

3.1. Procedure

Two identical sounds were emitted from two loudspeakers in an anechoic room (Fig. 1 a) with the help of programmable equipment that included a sine wave generator, electronic switches, attenuators and power amplifiers. In the preliminary experiments reported in [1], the signals were pure tones, at four different frequencies; and we also obtained some data with bands of noise, in which case the source was a filtered random noise generated by a Hewlett Packard analyzer (35665 A). In the study presented here, we restricted the measurements to 4000 Hz tones.

There were two parts in the localization measurements. In the first part, both sounds were simultaneous (Fig. 1 b, left), with durations of 50 ms, and rise and fall times of 10 ms. A variable ongoing phase difference was inserted between the two electrical inputs to the loudspeakers (see Fig. 1 c), by means of two independent delay lines. The

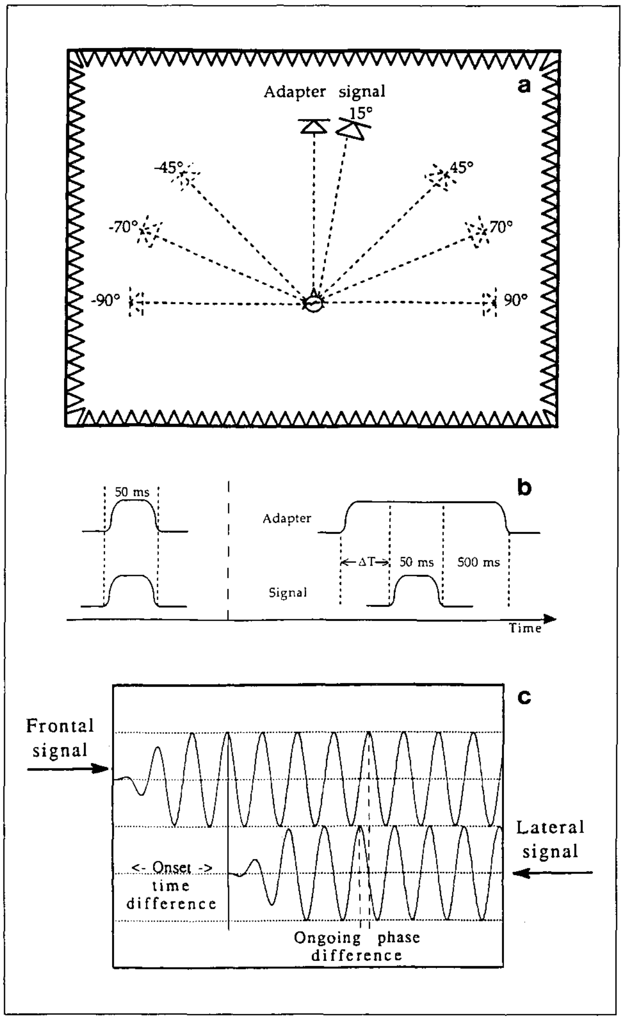

Fig. 1 a. Position of the loudspeakers relative to the listener, and possible azimuths of virtual sound sources.

Fig. 1 b. Envelope of the two signals; left: simultaneous beeps: right: delayed signals.

Fig. 1 c. Fine structures of the two signals.

delay lines were connected between the signal generator and the electronic switches that gated the sounds. The level and phase of each tone were measured separately, in the absence of the subject, at the position of the head. The level was 60 dB SPL for both tones.

The procedure used in this first experiment was the following. In a single trial, the subject was presented with three successive stimuli (pairs of simultaneous beeps, one beep from each speaker), at a rate of one pair every second; the three pairs were identical, with the same relative phase. Since the beeps were gated simultaneously, the resulting auditory event was a single fused sound. The subject reported the perceived azimuth of this fused sound. Then the phase difference between the signals was changed, a new series of three pairs was presented, a new azimuth estimation was made, and so on.

The phase difference was selected at random from trial to trial, within a limited set of discrete values. This limitation is due to the fact that the delays could only be set in 10-μs steps. Therefore, if we take the example of a 4-kHz tone, a full 360°-cycle of phase differences is equivalent to a range of delays of 250 μs, and this can be covered only in 25 steps of 10 μs, or 14.4 degrees (360°/25) each.

In the second part of the experiment, dedicated to the measurement of adaptation, the lateral sound was the same as above. However the frontal sound had a variable duration: it was turned on a certain time ΔT before the onset of the lateral sound, and switched off 500 ms after its offset (see Fig. 1 b right, and 1 c). The subjects had to tell the apparent direction of the 50-ms sound when it appeared, or at least the apparent direction of the auditory event created by the 50-ms lateral sound and the frontal sound together. The duration of the pre-exposure ΔT was the variable of the experiment. We tested the following values, expressed in ms: 20, 80, 150, 250, 500, 800, 1200, 2000, 5000 and 10000. During the 50 ms when both signals were on together (see central portion of Fig 1 b), there was no difference in their physical characteristics compared with the case where they were both pulsed (Fig. 1 a).

The measurements of perceived azimuth were made by direct estimation in degrees. To help the listeners make their judgements a series of labels were displayed around them, against the walls of the anechoic room, indicating the azimuths from 270° (to their left) to 90° (to their right), in steps of 15°. Intermediate values had to be estimated by interpolation.

The subjects in this experiment were five trained listeners with normal hearing, one female and four males, in the range 25 to 51 years.

3.2. Results of localization measurements

The mean results of our five subjects appear in Fig. 2, for pairs of simultaneous tones at 4 kHz, as a function of the phase difference between the two tones of the pair. Since four of the subjects repeated the measurement four times and the last one twice, each data point on Fig. 2 is the average of eighteen estimates. The square symbols at the top of Fig. 2 indicate the actual azimuth of the two loudspeakers, that is 0° and 15° respectively. The filled circles represent the estimated azimuth of the virtual source resulting from their simultaneous emission, the horizontal error bars showing plus and minus one standard deviation of the means. It can be seen that, as the phase difference between the two sounds varies from 0 to 360°, the apparent azimuth moves over a range of about +60° to −60°, with a certain variability among subjects. This result is in good agreement with those of a previous study by Canévet [22].

The results from the second part of this location experiment concern the effect of a possible auditory adaptation, due to a pre-exposure to the frontal sound, on the apparent azimuth of the compound lateral + frontal sound. As mentioned above, it appeared very soon that this effect depended very much on the phase difference between the sounds. Therefore, we made our measurements for different settings of the delay line. The results

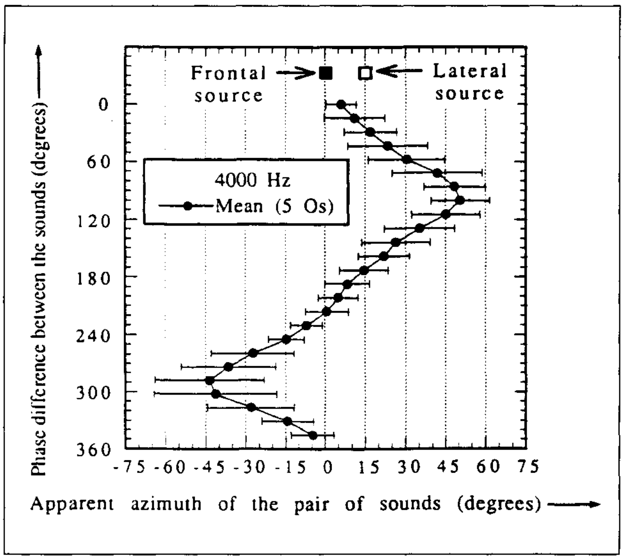

Fig. 2. Variation of the apparent azimuth (horizontal axis) of the simultaneous 4-kHz beeps (as depicted by Fig. 1 b, left) as a function of the phase difference in their fine structures (vertical axis). Mean judgments of five observers and standard deviations. The square symbols at the top of the picture indicate the actual azimuths of the two sources.

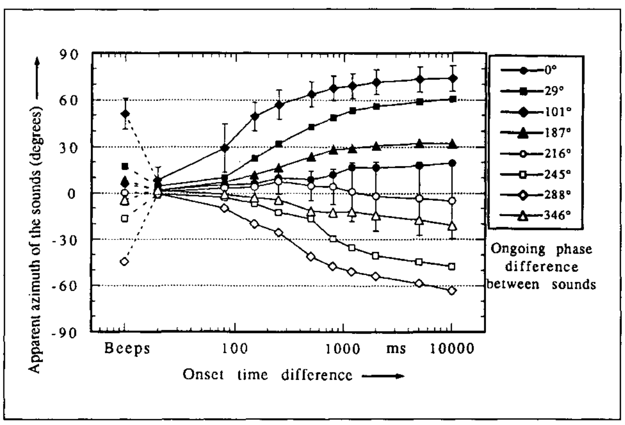

Fig. 3. Effect of a pre-exposure to the frontal sound on the apparent azimuth of the 50-ms beep, for various ongoing phase differences.

of the same five subjects are presented in Fig. 3, where each data point again corresponds to the arithmetic mean of eighteen judgements. The set of phase differences used appear in the frame to the right of the picture. Error bars are reported for two conditions only, to avoid overloading of the figure.

On this Fig. 3, the points located at an abscissa of 10, noted "Beeps", are data points taken from Fig. 2, for the corresponding phase differences. They are used as reference points, to remind us where the auditory image is perceived when the sounds are simultaneous. They should not be connected to the points at 20 ms, since they are from a different experiment. Nevertheless we drew this connection (in dashed lines) to show the recentering effect obtained for small values of pre-exposure time. This centering must be due to the precedence effect: for onset time differences (ΔT) as small as 20 ms between the frontal and lateral sounds, the perceived azimuth is imposed by the leading (frontal) sound. On the other hand, when ΔT is extended to durations longer than 100 or 200 ms, a progressive displacement of the 50-ms signal is observed, in some conditions.

At this point, it is worth making a short digression about the variation in the auditory events experienced by the subjects on different successive presentations, that is for different values of ΔT. As mentioned earlier, the two sounds are heard as one single beep when they are simultaneous; this was the case for all the data points in Fig. 2. For ΔT's longer than 200 ms or so, the 50-ms signal was heard separately, as a different event, especially when its apparent direction was different from the front. Finally, for values of ΔT around 20 or 50 ms, the region where the precedence effect is expected to play a role, the lateral sound was perceptually integrated with the frontal sound. We could say that it was heard as a temporal alteration of the frontal sound, and therefore localized somewhere in the frontal direction.

It is also important to indicate that, in this part of the experiment, the acoustic field created at the subject's ears by the two sounds during the 50 ms when they are simultaneous (central interval of Fig. 1 b, right picture) does not change as the duration of the pre-exposure ΔT is varied. That was checked by physical measurements made before we started to collect the psychoacoustical data. In other words, the interaural level difference remains the same, for one given value of the ongoing phase difference, whatever the value of ΔT. Therefore, the variation in azimuth, when observed, must correspond to a variation, in the auditory system, of sensitivity to those interaural differences. Let us consider, for example, the upper curve of Fig. 3 (filled diamonds), that corresponds to a phase difference of 101° in the fine structure of the signals. For simultaneous 50-ms sound (Beeps), the apparent location of the fused image has a direction of about 50°. The same value is found again, for non-simultaneous sounds, when ΔT is of the order of 100 ms. This could be seen as the temporal limit of action of the precedence effect; but when ΔT is increased beyond 100 or 200 ms, the apparent azimuth keeps increasing, up to an average of about 75°. The effect is even bigger in the condition represented by the filled squares (phase difference of 29°), where the azimuth varies from about 20°, for the isolated beeps, to 60° after a 10-s period of adaptation to the frontal sound. On the other hand, there are conditions where the azimuth varies only a little (filled circles, empty circles and empty triangles); these correspond to phase differences for which the beeps are localized close to the centre.

Individual differences can be high in this experiment. For example, in the condition represented by the empty circles (Fig. 3), the final estimates have a standard deviation of 20°. This may be due in part to the extreme sensitivity of the effect to the phase difference between sounds. As we noted above, the phases were measured at the place of the head in the absence of the subject. There is a possible variability in the position that the subjects had, relative to the loudspeakers, from session to session. The consequence would be a possible variability among subjects in the actual phase difference at their two ears.

To avoid this source of variability, related to the experimental conditions, we decided to run the same type of experiment under earphones.

4. Lateralization experiments

4.1. Experimental conditions

To simulate with earphones the localization experiment reported above, we used the following arrangement (see Fig. 4). First of all, the frontal sound was simulated by a diotic signal, obtained by feeding in parallel the two earphones from the same sine wave generator. The lateral sound was simulated by a dichotic signal, in which a delay of 70 µs (τ' in Fig. 4) was inserted in the left channel by means of a delay line. Finally, the ongoing phase difference between the two signals was created, as in the case of the localization experiment, by an extra delay line (τ) connected between the sine generator and the electronic switches. The two signals were then summed in an electronic mixer connected to the earphones.

These lateralization measurements were made in a sound-proof room, for 4-kHz pure tones; the levels were set to 65 dB SPL for each tone separately on each earphone. As in the case of the localization experiment, there were two parts in this experiment. In the first part, the intracranial localization of pairs of 50-ms tones was measured. The tones were simultaneous, and they had the same rise/fall times of 10 ms. Only the phase difference (τ) between the two signals was varied from one presentation to the next. For each value of the phase difference, the pair of sounds (diotic plus dichotic) were presented three times, at a rate of one per second, and the subject had to report the apparent position within the head of the resulting auditory image. To help the subjects make their estimations, a picture was presented on the terminal screen (VT 320), somewhat similar to that which appears at the bottom of Fig. 4, showing a horizontal line graduated from -6 to $+6$, these values corresponding to the left and right earphones respectively, zero being the centre of the head.

After this measurement, there was a pause that lasted several minutes. Then the second part of the experiment started, to measure the effect of adaptation. In this part, the diotic sound was turned on first, and left on for the entire measurement. After 5 s of exposure to the diotic tone, three pairs of 50-ms dichotic tones were presented, at the same rate of one every second as above. The subjects were asked to tell the apparent position of these three signals. Then a new triplet was presented, and so on. The phase difference between the diotic and the dichotic signals was selected at random between two successive presentations.

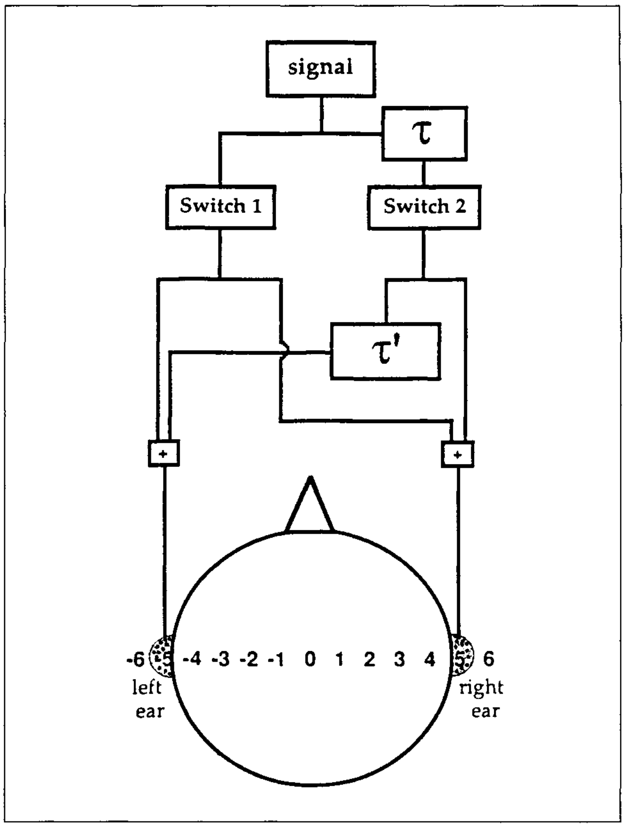

Fig. 4. Schematic diagram of the experimental arrangement used for the lateralization measurements.

Five male subjects participated in this experiment; four of them were the same as those of the preceding experiment.

4.2. Results

Given the arrangement that we used, the summation of the diotic and dichotic signals leads to different voltage levels at the input to the two earphones, and therefore to different sound pressure levels at the subject's ears. These sound pressure levels are presented in Fig. 5a as a function of the phase difference between the signals. As one can deduce from this picture, the resulting interaural level differences vary from about -25 dB (left side more intense) to $+25$ dB as the phase difference is varied by a complete cycle of 360°. With such interaural differences, the apparent position of the auditory image moves from one ear to the other, in a way which is very much equivalent to what was found in the free-field localization experiment. This is what is shown by the experimental data of Fig. 5b (unfilled circles). In this figure, representing the lateralization of simultaneous beeps, each data point is the arithmetic mean of ten judgments (two per subject). With a phase difference around 0° or 360° (left and right parts of Fig. 5b respectively), the beeps are heard close to the centre of the head, slightly to the right though, because of a small level difference resulting from the effect of τ'. Then, as the phase difference is varied, the apparent

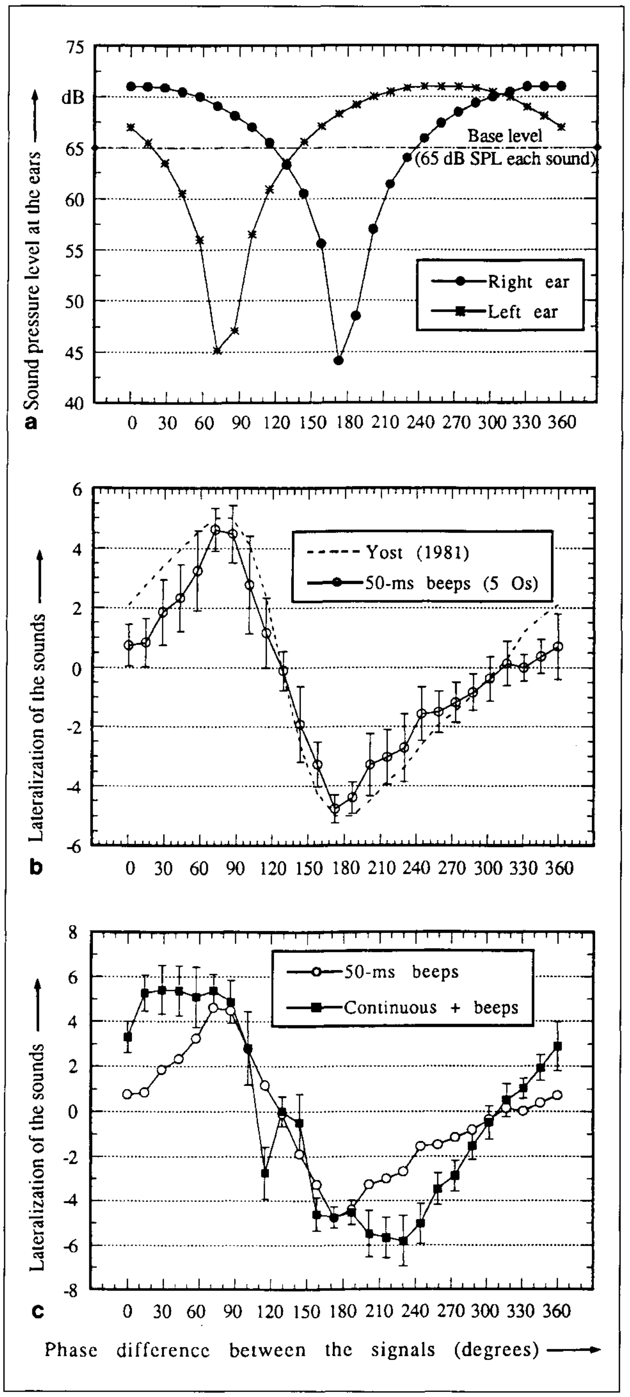

Fig. 5 a. Sound pressure levels on the right and left earphones for the arrangement described by Fig. 4, as a function of the phase difference (τ) between the diotic and the dichotic signals. Each signal alone produces a sound pressure level of 65 dB.

Fig. 5 b. Lateralization of simultaneous 50-ms beeps (unfilled circles), as a function of the phase difference in their fine structures. The dashed line is an empirical curve taken from a study by Yost [23].

Fig. 5 c. Lateralization of the beeps in the presence of a continuous stimulation to the diotic tone (filled squares), as a function of the phase difference in the fine structures. The unfilled circles are the same as in Fig. 5 b.

location of the image moves from − 6 to + 6, that is from the left to the right ear.

These results are in fairly good agreement with those of earlier studies. We borrowed from Yost [23] an empirical curve (fitted to experimental data; see also Yost and Hafter [24]) that gives the perceived location of dichotic pure tones as a function of their interaural level difference. Adapted to our own level differences (deduced from Fig. 5 a), this curve becomes the dashed line in Fig. 5 b. There is a slight discrepancy between our results and that curve: our data points tend to be shifted towards the middle line (centre of the head). This may come from a difference in the procedure. In Yost's experiment, the subjects had a pointer to indicate the location of the auditory image on a picture representing the head. Besides, the stimulus used for each presentation was a train of three beeps with no interaural difference, immediately followed by five dichotic test beeps that included a level difference. The first three beeps gave a reference to the subject for the centre of the head, and the estimation of the position of the lateral sound then became a differential measurement, increasing the precision of the judgments, especially for sound located around the midline. Nevertheless, for most points, the smoothed curve falls within the standard deviations of our data.

In the case of a continuous diotic stimulation, the second part of the measurement (filled squares, Fig. 5 c), two interesting effects are created. The most striking for the listener, and still not perfectly understood, is the sensation of hearing double images, one on each ear, for phase difference values from about 90° to 180°. For the other values, the usual impression was that of a single image, even in the presence of the continuous background. Since they were asked to give a single response in all cases, the subjects had to choose, in cases of a double image, the one that had the higher loudness. This resulted in a distribution of points that were concentrated on the right or on the left side, and sometimes in the middle. This is the reason why the standard deviations are so big in this interval (90° – 180°, Fig. 5 c). We do not have an explanation yet for these double images, but we noticed that the range of phase differences for which the effect occurs is the one where the average level on the two ears is the lowest (see Fig. 5 a, for phase differences between 90° and 180°).

The second observation that we can make is that, except for the region where double images appear, the burst of dichotic sounds are almost always located towards the side (filled squares compared to unfilled circles in Fig. 5 c), as was the case in the free field experiment. This is especially clear for phase differences between 0° and 90° for example, where the sounds are localized to the right (mean judgment of about + 5), that is beyond what is observed without adaptation. The same effect is found in the interval of 180° to 360°, if we except the region around 310° where the judgements are close to zero for both conditions. Finally, it is noteworthy that the judgements are displaced toward the left (from 200° to 300°) or towards the right (beyond 330°) depending on the reference position of the images without adaptation.

5. The time dependence of the adaptation effect

The experiment described in paragraph 4 compared the results of two extreme conditions. In one of them, the two sounds were pulsed and presented simultaneously, so there was no pre-exposure to the diotic tone and no adaptation was to be expected. In the other condition, the diotic sound was continuously on for the entire measurement; this probably induced a maximum amount of adaptation. One interesting question is how this amount of adaptation varies between the two extremes (from no adaptation at all to maximum adaptation), as a function of the duration of the leading diotic sound. The following experiment addresses this question.

5.1. Procedure

To determine this time dependence of the adaptation effect for lateralization, we performed an experiment of the same type as the one reported in paragraph 3.1 (Fig. 3) for localization. The signals in this experiment had the sequence described in Fig. 1 b (right picture), except that the two tones ended simultaneously. The rise and fall times were set to 5 ms. The following values of ΔT were used: 5, 10, 50, 100, 500, 1000 and 2000 ms. As in Fig. 3, we selected a limited number of phase differences between the sounds (variable in Figs. 5 a to 5 c) namely 14.4, 43.2, 57.6, 201.6, 230.4 and 259.2 degrees. To these values correspond the following interaural level differences (see Fig. 5 a): 5.5, 10, 14, -13, -6.9, and -3.6 dB respectively, for a nominal level of 65 dB SPL for each tone separately.

The same five subjects as in the experiment described in paragraph 4.1. participated in this one. Since this experiment was conducted about five months later than the previous one, we ran the subjects once again on the same two "control" conditions (simultaneous pulses and continuous inducer). No significant difference was found between the two series of results.

Then we ran the main experiment, with the phase differences and the ΔT's listed above. These two parameters were varied at random during the experiment. More precisely, we first selected at random one given value of ΔT, and then ran the six phase differences (or interaural level differences, ILD) at random also. Therefore, each trial consisted in one single presentation of the two sounds with one given ΔT and one given ILD. After each presentation, the subject entered an estimation of the apparent lateralization of the test tone, and there was a pause of 2 s before the next presentation. Once the six values of ILD had been presented, at one given ΔT, a new value of ΔT was chosen and another series of six ILDs was run, and so on. The whole session was repeated once, after one or two days, for every subject.

5.2. Results

The results of these measurements appear in Fig. 6, where the mean lateralization judgements are displayed as a function of the onset time difference between the diotic

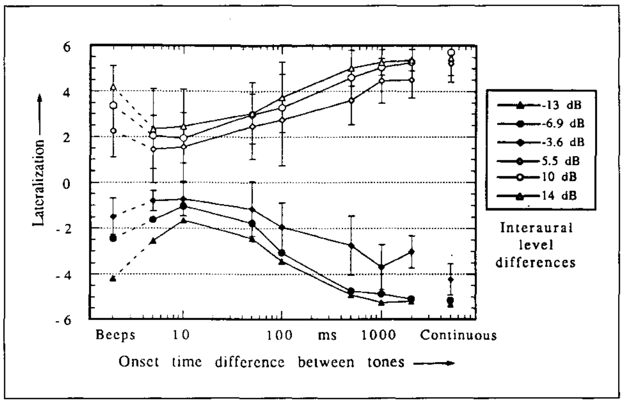

Fig. 6. Effect of a pre-exposure to the diotic tone on the lateralization of the dichotic tone for various interaural level differences. Mean results of five observers.

and the dichotic sounds. The two extreme conditions mentioned above, in the introduction of this paragraph 5, are named "Beeps" and "Continuous" respectively. The interaural level differences, (ILDs), are shown in the frame on the right of the picture. The error bars are drawn for some conditions only, for reasons of clearness, but the standard deviations were about the same at all ILDs.

These results confirm the ones presented on Fig. 3, corresponding to the localization measurements. On the left side of Fig. 6, it can be seen that the auditory images tend to concentrate towards the centre for small values of ΔT. The effect is strongest for $\Delta T = 10$ ms, but the phenomenon is effective over a duration of the order of 100 ms. For the higher values of ΔT, the limit is clear. It seems that the final, or extreme, lateral position of the image is not reached yet after 2 s. Therefore, the duration of the exposure which is necessary to reach a maximum of adaptation is longer than 2 s. This is consistent with the data on detection [5, 6] and on localization (Fig. 3), which altogether seem to suggest that complete adaptation requires a pre-exposure duration of the order of 10 s or more.

6. Recovery from adaptation

Once we know how long it takes for adaptation to be established, another important question is how long it takes to disappear. As we mentioned in paragraph 2, if we rely on the data in the literature, or even on our own preliminary data [1], this recovery time seems to vary considerably among subjects. To clarify this question, we undertook a specific experiment, that we ran in parallel with the one above, and with a procedure which is quite similar to the one used in this previous experiment.

6.1. Procedure

The sequence of the signals was the following. First, the subjects (they were the same five as above) were presented with a 2-s diotic tone at 65 dB SPL. Then there was a gap

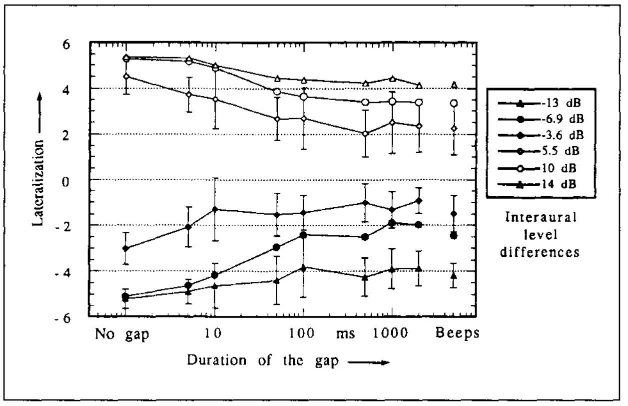

Fig. 7. Lateralization of pairs of beeps, presented after a 2-s exposure to the diotic tone alone and a silent interval (gap). The duration of the gap is the variable and the interaural level difference of the pairs of beeps is the parameter. Mean results of five observers.

of δT ms, which was the variable of the experiment. Finally, a pair of simultaneous beeps (diotic plus dichotic) was presented, right after the gap. Rise and fall times were also 5 ms. The durations of the gaps, that we call δT to avoid possible confusions with the adaptation variable ΔT, were: 0, 5, 10, 50, 100, 500, 1000 and 2000 ms. They were selected at random. For each of them, the same six values of phase difference (or interaural level difference) were used as above. They were run at random too, within one δT condition. The condition where $\delta T = 0$ ms is in fact equivalent to the case where $\Delta T = 2$ s in the preceding experiment.

6.2. Results

The most important point in our results (Fig. 7) is that the recovery is quite fast, and that it does not vary very much among the listeners. At least, this is true with the group of listeners that we had, and under the conditions that we ran. The isolated data points on the right of Fig. 7 are taken from Fig. 6 and correspond to the simultaneous beeps with no onset time difference. The points corresponding to a gap of 0 ms ("No gap" on the figure) are located at an abscissa of 1, because of the logarithmic horizontal scale. As in Fig. 6, the ILDs are indicated in the frame for the six different conditions.

On most of the curves, it appears that the silence interval that is necessary to recover from the adaptation by 2 s of exposure to the diotic tone is about 500 ms. The standard deviations are not very big, and are more or less the same for all conditions. We included them only in three of the curves.

7. Conclusion

The measurements performed under earphones confirm the results of the free-field experiments: a prolonged exposure to a continuous sound may have an effect on the apparent direction of a subsequent sound. In general, if this sound comes from the side, it is shifted more towards the side, away from the direction it would have without exposure. If it comes from somewhere around the midline, there is almost no variation of its azimuth. In other words, the more lateral the auditory image is (or the higher the interaural level difference), the stronger the effect.

From the time dependence of the azimuthal variations, we assume that the mechanism underlying this effect is a form of "mean-term" adaptation, somewhat similar to what was found in increment detection in a pedestal. As the onset time difference between the pedestal and the increment is increased, the detection becomes progressively easier. The optimum detection is asymptotically reached after a duration of the order of 5 to 30 s, depending on the experimental conditions.

In the case of localization (or lateralization) it seems that, as the duration of the simulation by the leading sound is increased, the auditory system becomes more sensitive to interaural level differences. Then, when a second sound appears from the side, with a certain delay relative to the first one, it looks as though its interaural level difference increases as this delay increases.

More experiments should be done now, both in psychoacoustics and in physiology, to measure adaptation separately on both ears or at higher levels in the auditory system, under the same conditions of stimulation as in our lateralization measurements, in order to understand better the mechanisms of this type of adaptation, and the neural structures where it takes place.

References

[1] Canévet, G., Meunier, S., Auditory adaptation and localization. Acustica **80** [1994], 311–314.

[2] Meunier, S., Canévet, G., Adaptation auditive et localisation. 3ème Congrès Français d'Acoustique, Toulouse, 2–6 mai 1994, Journal de physique IV, colloque C5, supplément au journal de physique III **5** [1994], C5-395/398.

[3] Scharf, B., Loudness adaptation. In: Hearing Research and Theory, Vol. 2, Tobias, J. V., Schubert, E. D. (Eds.). Academic Press, New York, 1983.

[4] Canévet, G., Scharf, B., Botte, M.-C., Loudness adaptation: when and why it occurs. 13th Internat. Congr. Acoust., Belgrad, August 1989, 381–384.

[5] Scharf, B., Canévet, G., Ward, L., On the relation between intensity discrimination and adaptation. 9th International Symposium on Hearing. In: Auditory Physiology and Perception, Cazals, Y., Demany, L., Horner, K. (Eds.), Pergamon Press, Oxford, U.K., [1992], 289–295.

[6] Meunier, S., Marchioni, A., Détection d'un incrément d'intensité à différents niveaux et différentes fréquences. 2ème Congrès Français d'Acoustique, Arcachon, 14–17 avril 1992, Journal de physique IV, colloque C1, supplément au Journal de physique III, Vol. 2, avril 1992, C1-213/216.

[7] Meunier, S., Marchioni, A., Effect of short-term and long-term adaptation on pure-tone detection. Submitted to Acta Acustica, April 1994.

[8] Flugel, J. C., On local fatigue in the auditory system. Brit. J. Psychol. **11** [1921], 105–134.

[9] Bartlett, F. C., Mark, H., A note on local fatigue in the auditory system. Brit. J. Psychol. **13** [1922], 215–218.

[10] Pattie, F. A., An experimental study of fatigue in the auditory mechanism. Amer. J. Psychol. **38** [1927], 39–58.
[11] Pattie, F. A., A further experiment in auditory fatigue. Brit. J. Psychol. **20** [1929], 38–42.
[12] Thurlow, W. R., Jack, C. E., Some determinants of localization-adaptation effects for successive auditory stimuli. J. Acoust. Soc. Am. **53** [1973], 1573–1577.
[13] Thurlow, W. R., Marten, A. E., Perception of steady and intermittent sounds with alternating noise-burst stimuli. J. Acoust. Soc. Am. **34** [1962], 1853–1858.
[14] Elliott, D. N., Geula, C., Deer, B., Adaptation, lateralization, and loudness balancing. Unpublished manuscript [1979].
[15] Botte, M.-C., Baruch, C., Scharf, B., Loudness reduction and adaptation induced by a contralateral tone. J. Acoust. Soc. Am. **80** [1986], 73–81.
[16] Wakefield, G. H., Perceived azimuth in multiple source acoustic environments. Ph.D. Dissertation, University of Minnesota 1988.
[17] Weerts, T. C., Thurlow, W. R., The effect of eye position and expectation on sound localization. Perception & Psychophysics **9** (1A) [1971], 35–39.
[18] Krauskopf, J., Figural after-effects in auditory space. Amer. J. Psychol. **67** [1954], 278–287.
[19] Bodden, M., Meunier, S., Untersuchungen zur Detektion und Lokalisation von Intensitätsinkrementen in schmalbandigen Signalen. Fortschritte der Akustik, DAGA 1993, DPG GmbH, Bad Honnef, 832–835.
[20] Bertrand, M. P., Aspects of binaural experimentation. Proc. Roy. Soc. Med. **65** [1972], 809–810.
[21] Moss, P. J., Adaptation effects of imbalanced interaural parameters on lateralization judgements. Unpublished B. S. manuscript, M.I.T., June 1977.
[22] Canévet, G., Aspects physiques de la détection et de la localisation masquées. Acustica **57** [1985], 122–132.
[23] Yost, W. A., Lateral position of sinusoids presented with interaural intensive and temporal differences. J. Acoust. Soc. Am. **70** [1981], 397–409.
[24] Yost, W. A., Hafter, E. R., Lateralization. In: Directional Hearing, Yost, W. A., Gourevitch, G., (Eds.). Springer-Verlag, New York 1987, 49–84.