Effect of stimulus distribution on the buildup of contextual plasticity in sound localization

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Abstract

Contextual plasticity (CP) is a short-term adaptation effect in sound localization (Kopco et al., 2007). CP is exhibited by biases in localization of click stimuli in target-alone trials when, on interleaved contextual trials, a distractor-target click pair is presented. In previous CP studies, a gradual drift in localization responses towards the front was observed. The drift was not attributable to CP but can potentially confound its analysis. Here, we analyze several CP data sets with various distributions of contextual and target-alone stimuli in order to test whether the drift is related to asymmetry in the distribution of the stimuli relative to the subject's midline. The results show that the drift tends to have a steeper slope when the stimulus distribution mean is more lateral, confirming that it is likely related to the distribution asymmetry.

1 Introduction

The perceived location of a sound source can be affected by sounds heard shortly prior to the sound of interest. One example is the precedence effect (for review, see Litovsky et al., 1999), in which presenting an identical sound a few miliseconds ahead of the target induces a percept of only one fused sound coming from the direction of the first of the sounds. Another example is when the target sound is preceded by a longer-lasting "adaptor" sound, resulting in localization shifts away from the adaptor location (e.g., Carlile et al., 2001; Kashino & Nishida, 1998).

Here, we examine another form of adaptation, referred to as *contextual plasticity* (CP), in which the perceived location of a target is affected not only by a single preceding stimulus but by stimuli presented within a broader temporal window. CP was first observed in a study by Kopco et al. (2007). In that study, trials in which only the target stimulus was presented were randomly interleaved with trials in which the target stimulus was preceded by an identical distractor stimulus (presented from a fixed location, either frontal or lateral). Unexpectedly, responses on target-alone trials were found to be affected by the location of the distractor in the interleaved trials, being more frontal when distractor was lateral and vice versa (i.e., the responses were shifted away from the distractor location). The inducement of contextual biases was confirmed in several other CP experiments in which CP was evaluated relative to a baseline condition only containing target-alone trials (Andrejkova et al., 2016; Tomoriova et al., 2014; Kopco et al., 2015).

However, the previous CP studies also revealed that responses, including those from a reference baseline condition with no distractor, tend to gradually drift towards the listener's straight ahead (azimuth 0°). The cause of these drifts is not yet understood and its examination is important for the CP analyses, e.g., to clarify to what extent gradual changes in responses relative to baseline responses correspond to buildup/decay of CP and to what extent they are altered by the (potentially also context-dependent) drift.

In the current study, we analyze datasets from several previous CP experiments in order to examine the drifts for different context conditions. Based on preliminary analyses (described in more detail in subsection 3.2 Preliminary analyses below) we hypothesize that the drifts are a consequence of the fact that the sound stimuli are not distributed around straight ahead where the localization acuity is the highest (Makous & Middlebrooks, 1990), but at the side. Assuming that the spatial distribution of incoming sounds is approximately uniform (perhaps with stimuli coming from the median plane being more likely since we tend to face the stimulus of interest), and that the spatial representation of the stimulus acoustic cues (ITD and ILD) covers the range of -90° to +90°, the mean of the distribution of the stimuli can be a priori expected to be 0°. Then, in the current experiments in which stimuli are presented from one quadrant (e.g., from 0° to 90° with mean at around 45°), it is likely that the spatial auditory representation adapts to map this limited range to the a priori expected range of -90° to 90°, thus causing a drift in the perceived location of the stimuli. Such adaptation has been hypothesized for auditory (Maddox et al., 2014) and visual (Grossberg, 1982) spatial representations, resulting in improved spatial resolution, and it's been demonstrated for ILD representation (Dahmen et al., 2010). Based on this hypothesis we expect that the more lateral is the bias in distributions of stimuli, the larger drift in temporal data towards midline will be observed. In this analysis we assume that each type of stimulus (distractor, target from a target-alone trial, target from a context trial) contributes equally to this effect since the stimuli are identical in their acoustic properties.

2 Methods

We performed analyses on data from four previous CP experiments. The experiments are described here only briefly, more details can be found in following publications: Exp1: Kopco et al. (2007), Exp2: Andrejkova et al. (2016), Exp3&4: Tomoriova et al. (2014). (Note: one experimental condition from Exp 4, with stimuli centered around azimuth 90 degrees was omitted from analyses in this paper, because of possible confounds related to front-back confusion errors - see, e.g., Makous and Middlebrooks, 1990).

2.1 Previous experiments

In each experiment, the subject was seated in a classroom or anechoic room (Exp 1&2) or acoustic booth (Exp 3-4) and was surrounded by 9 loudspeakers arranged uniformly in a quarter-circle arc. The orientation of the listener relative to the speaker array, as well as the distribution of stimuli across the speaker array, changed across different experimental conditions and experiments (see Fig. 1 for an example of setup used in Exp 3, and Fig. 2 for distributions of stimuli in each condition of each experiment). Symmetric conditions for left and right orientation of speaker array relative to the listener were tested but in all presented analyses data are collapsed across orientation.

The subject's task was to point with a hand-held pointer to a perceived location of a target sound. *Experimental runs* contained a mixture of "target-alone" trials in which only the target was presented and "contextual trials" in which the target was preceded by an identical distractor. Additionally, Exp 3&4 contained reference *baseline runs* consisting of target-alone trials only. Experimental runs in Exp 3&4 started and ended with several pre-adaptation and post-adaptation trials intended to examine the buildup/decay of adaptation after onset/offset of the contextual trials.

Two-ms frozen noise bursts ("click" stimuli) were used as target stimuli in all experiments. In a majority of the experiments, the distractor was identical to the target. However, in a subset of contextual trials of Exp 2 the 1-click distractor was replaced by an 8-click distractor. Table 1 along with Fig 2. summarizes basic information about the experiments.

	baseline condition	distractor type
Exp 1	not included	1-click
Exp 2	not included	1-click / 8-click
Exp 3	included	1-click
Exp 4	included	1-click

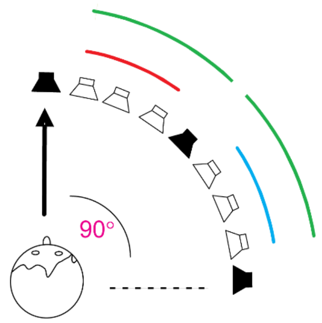
Tab. 1: Summary information about the differences in design and stimuli across the experiments. Differences in distributions of stimuli are summarized in Fig. 2.

2.2 Analyses of the drift

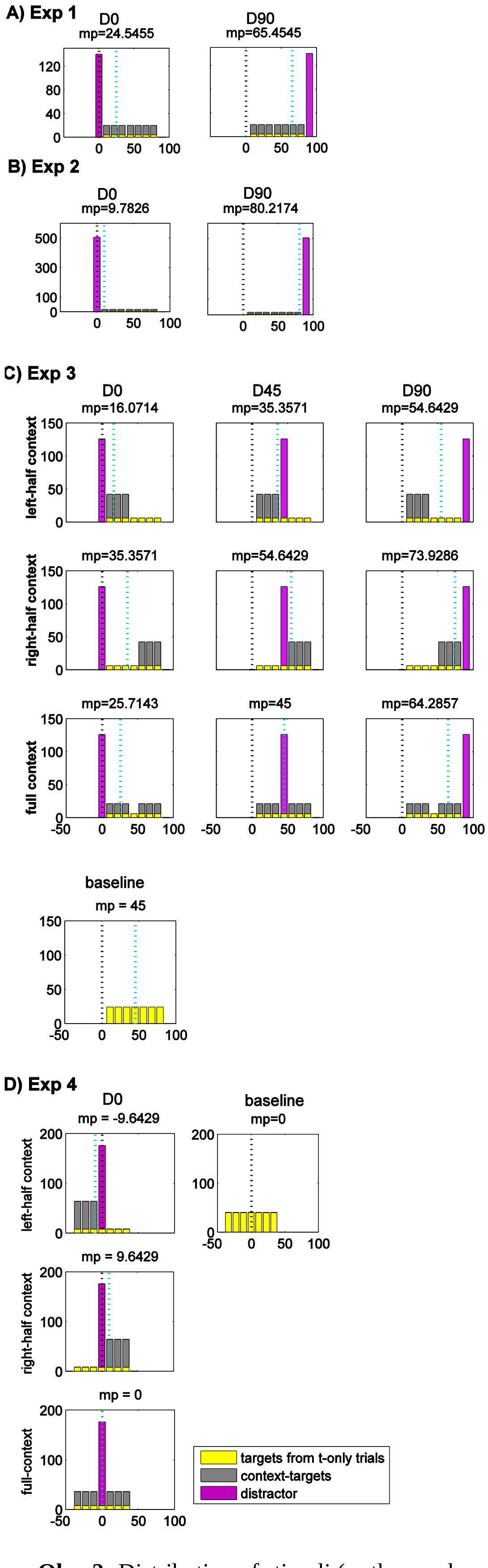
In order to evaluate how slope of the drift depends on the laterality of the distribution we computed the mean stimulus lateral position in degrees (*mp* value in Fig. 2) for each condition as the weighted mean of stimulus locations used in that condition (each location was weighted by the number of stimuli presented from that location), and fitted the temporal profile data for each subject and condition (across-subject average of these data is shown in Fig. 2) by the linear function:

$$y = k * x + q$$

in which y corresponds to an estimate of the response bias relative to the actual target location (i.e., localization error) averaged across all target locations, x corresponds to a subrun number (trials were grouped into subruns in this analysis; one subrun corresponds to 42 trials in Exp 1, 35 trials in Exp. 2 and 28 trials in Exp 3&4) within the adaptation part of the run, and parameters k and q represent the slope of the temporal drift and its offset, respectively.
Only the responses from the target-alone trials are considered in the analyses of the drifts.



Obr. 1: Experimental setup for the Exp. 3. Black loudspeakers indicate possible distractor locations (only one distractor location was used in each experimental run), while target could be presented from each of the 7 inner loudspeakers (in target-alone-trial targets) or was restricted to specific subregion of the speaker array (in contextual trials) in left-half/right-half/full-context condition (coded here and in other Exp 3&4 figures by red, blue and green color , respectively).



Obr. 2: Distribution of stimuli (as the number of stimuli per location) in different experimental conditions. X-axis shows stimulus lateral angles with 0° corresponding to straight ahead (depicted by black dotted line). Blue dotted line indicates the mean stimulus lateral position (*mp*). Proportion of different types of stimuli is depicted in each bar by different color (distractor: pink, target-alone-trial target: yellow, context-target: grey). For the 8-click distractor used in Exp 2, each click is considered as a separate stimulus.

3 Results and discussion

3.1 Distributions

The distributions of stimuli in each experimental condition (with pre- and post-adaptation trials excluded) from the experiments are plotted in Fig. 2. Different colors correspond to different types of stimuli (pink: distractor, grey: context-targets, yellow: target-alone-trial targets). Mean lateral stimulus position value computed from a distribution of stimuli is depicted by dotted blue line, while straight ahead position is depicted by dotted black line. Conditions identified by this analysis as similar in terms of their similar mean stimulus lateral position value are D0 condition from Exp 1 and D0 full-context condition from Exp 3, and similarly for D90. In Exp 3, identical *mp* value was found for two conditions with largely different number of stimuli per identical location, specifically, D0: right-half context vs D45:left-half context, and D90 left-half context vs D45: right-half context.

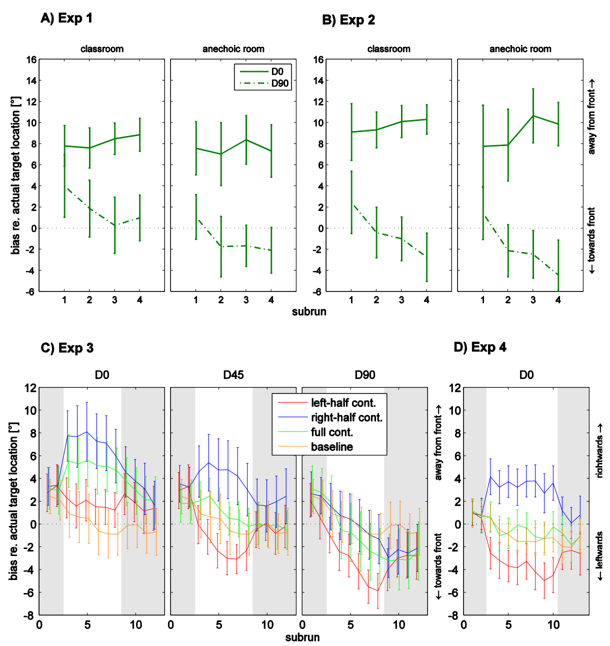
3.2 Preliminary analyses: Temporal profile of adaptation during a run

Analyses in this section are provided to illustrate a potential confounding effect of the drift on CP analysis and explain in more detail the motivation to examine drifts as a function laterality of the distribution.

Fig. 3 shows biases in subjects' responses during the course of the run, averaged across the target locations. For both Exp 1&2, results are plotted separately for each acoustic environment (classroom or anechoic room). In both environments and both experiments, when the distractor was frontal (solid lines), responses had approximately constant or slightly increasing bias of approx. 8 to 10 degrees away from the distractor. When the distractor was lateral (dash-dotted lines), responses were initially biased by up to approx. 4 degrees but during experimental run they drifted away from the distractor location (towards subject's straight ahead). The drifts were more pronounced for Exp 2 where 8-click distractor was used on some contextual trials instead of 1-click distractor.

This pattern of results might indicate that 1) for 8-click distractor the buildup of CP lasts longer and saturates at larger magnitudes, and 2) lateral distractor induces larger CP. However, data from Exp 3&4 indicate a different explanation of this effect. Conditions comparable to those from Exp 1in their distribution of stimuli are Exp3 D0 and D90 full-context conditions (green lines in first and third panel; see also Fig. 2 for the corresponding distributions). Despite minor differences in initial magnitudes after the start of the adaptation part (white region), similarly to previous two experiments, frontal distractor responses are approximately constant while lateral distractor responses gradually drift towards the front. However, the drift can be observed also in the remaining conditions, and, in particular, in the baseline condition (orange line), indicating that the drift cannot be explained solely by the presence of the distractor (i.e., solely by CP effect).

But in conditions in which distractor is present, an increase in laterality of the distractor tends to increase the negative value drift (compare drifts across different columns of Exp 3) and dash-dotted vs solid lines in Exp 1&2. In the following section, we evaluate this effect.



Obr. 3: Temporal profile of adaptation for different experimental conditions. Across-subject mean (+-standard error of the mean) bias relative to actual target location, averaged across all target locations, is plotted as a function of subrun. Conditions differing in distractor location (D0, D45 and D90) are plotted in separate columns while conditions differing in context-targets locations are plotted as colored lines within the same subplot. (i.e., similar layout as in Fig. 2 except that each colored line here corresponds to a separate row in the corresponding experiment's subplots of Fig. 2). Shaded regions indicate pre- and post-adaptation part of the run in which only target-alone trials were presented, white region indicates adaptation part in which target-alone trials were interleaved with contextual trials.

3.3 Effect of mean stimulus lateral position on slope of the response drift

Fig. 4 shows across-subject mean slope for different *mp* values, i.e., how slope of the drift changes with increasing distance between the mean of the actual distribution and the position straight ahead.

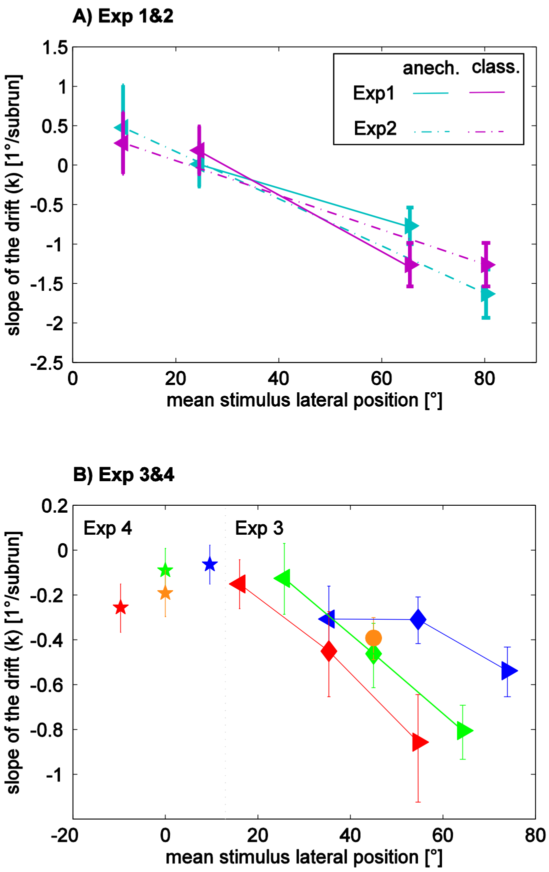
In Exp 1&2, k values range from approx. -1.5°/subrun for *mp* values farther from straight ahead (conditions with lateral distractor, depicted by right-pointing triangle symbols) to approx. 0.5°/subrun for *mp* values closer to straight ahead (conditions with frontal distractor, depicted by left-pointing triangle symbols). Datapoints from the same experiment and acoustic environment, i.e., which are the most comparable, are interconnected. In all of them, *k* value becomes more negative with increasing mean stimulus lateral position. (note: *mp* values between the two distractor conditions in Exp 2 are more distant from each other due to the fact that 8-click distractor was used on some trials, and it shifted the mean of the distribution towards its location).

Interesting observations are a slightly positive *k* values for frontal distractor conditions. Their potential cause is the interference of the non-CP-related drift with longer CP buildup process, since the direction of the drift is consistent with CP buildup effect, i.e., away from the distractor.

In Exp 3&4, *k* values range from -1°/subrun to 0°/subrun. Even though the trends are similar to Exp 1&2, these results also show that the effect occurs only between conditions which differ only in distractor location, with their context-targets locations being identical, not vice versa, where the slope value for some distractor locations even increases to less negative values (compare the datapoints plotted with different symbols of the same color versus those plotted with different colors but same symbol; e.g., compare a change in the slope between the three points of a green line vs change in the slope between the three diamonds). A different pattern for the blue line caused by the D0 right-half context condition (left-most blue triangle) might be related to several aspects of the data, e.g., the fact that for this condition, the biases are the largest in the lateral direction, thus requiring the most effortful response, or the fact that the target distribution is bi-modal (Fig 2).

For the conditions having the same *mp* value, k values do not differ in two cases (compare green and orange symbols at *mp* values of 0° and at 45°) but large difference is observed in one case (compare blue diamond and red right-pointing triangle at *mp* value of around 55°, corresponding to D45 right-half context and

D90 left-half context, respectively). The cause of this difference is not clear, but possibly can be explained based on CP effects, in the first case acting in the opposite direction as non-CP-related drift in responses (since CP in general acts in the direction away from distractor towards the side with context-targets, see Fig. 4), decreasing the slope to less negative values and in second case acting in the same direction, increasing the negativity of the slope.



Obr. 4: Across-subject mean and standard error of the slope of the linear fit (from the arctangented parameter *k*, then transformed back into *k* values in the plot), as a function of mean lateral stimulus location. Datapoints from conditions which differ only in distractor location are interconnected for better visualization. Distractor location is indicated by the marker symbol, with left-/right-pointing triangle corresponding to D0/D90 condition and diamond symbol corresponding to D45 condition. Stars symbol also correspond to D0 condition but with different orientation of speaker array relative to subject.

To quantify these observations, Pearson's correlation coefficient was computed between the *mp* values and the corresponding across-subject mean *k* values within each experiment. The results are summarized in Table 2. A significant correlation was found in all experiments in which it was expected, suggesting that the hypothesis is correct, even though it doesn't explain all aspects of the data.

	r	p
Exp 1&2 merged	-0.7341	**0.0381**
Exp 3	-0.7306	**0.0164**
Exp 4	-0.2701	0.7299
Exp 3&4 merged	-0.7598	**0.0016**

Tab. 2: Pearson's correlation coefficients and their respective p-value between the *mp* and mean k value (from Fig. 4) for each experiment or for the combination of experiments (if comparable).

4 Summary and general discussion

Previous analyses of temporal profile of localization responses during runs revealed that responses drift towards the front, also in the baseline condition in which no distractor was presented. Here, we analyzed these drifts, hypothesizing that they emerge from the fact that distribution of stimuli during an experimental run was offset from straight ahead where spatial acuity is the largest (Makous & Middlebrooks, 1990) and auditory system might try to optimally align the stimuli with neural representation in order to better discriminate between spatial locations of presented sounds. The results are in general consistent with this hypothesis, in a sense that responses drifted towards straight ahead and, on average, the data drifted more when distribution of stimuli were centered more laterally. (Note that the slightly increasing slope in Exp 1&2 for the frontal distractor was only negligible and might be caused by CP, since it has the same direction, i.e., away from the distractor. Similar explanation can be used for Exp 4 condition in which mean lateral stimulus position was slightly offset to the left of straight ahead but responses drifted away from straight ahead). However, several properties of the drifts were observed which need more detailed examination. First, when distractor location was kept constant and distributions differed only in context-targets locations, the increasing effect of mean stimulus laterality on the drift magnitude was not observed and in some conditions was even reversed (the slope of the drift became less negative for more lateral mean stimulus positions), but the change was on average smaller and less consistent compared to when context-targets locations were kept constant and location of the distractor varied. A possible explanation for this reversed effect is that the context-targets are always presented shortly (25-400 ms) after the distractor, i.e., the two sounds might perceptually interact (see Litovsky et al., 1999) and thus their effect on the overall stimulus distribution might be reversed or suppressed).

Another suggestion for further analysis, which would better separate CP effect from the aligning effect is to omit first adaptation subrun, during which CP effect might still build up. Alternatively, a new experiment can be designed in which localization will be examined for normal or uniform spatial distributions with no specific temporal patterns as in CP experiments. Finally, another partial contribution to the observed drifts might originate from the method of responding used in these experiments (i.e., pointing) which might cause that subjects gradually underestimate more lateral locations since pointing there requires more effort.

Acknowledgement

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