Auditory statistics development does not rely on vision, but the processing of sound local features is hampered by late-onset sight loss

Author list: Martina Berto[1], Pietro Pietrini[1], Emiliano Ricciardi[1], Davide Bottari[1]

Affiliations:

1 *Molecular Mind Lab, IMT School for Advanced Studies, Lucca, Italy*

Corresponding author
Davide Bottari
davide.bottari@imtlucca.it

Summary

The auditory system relies on both local and global representations to recognize different sounds. Because local features analysis is constrained by storage capacity, average statistics of these features are computed over time to generate compact representations at the expense of temporal details availability. It is unknown whether these processes are restricted to the auditory system or interact with other modalities, such as vision. To answer this question, we examined how statistical properties of sounds are affected by atypical development of the visual system. We tested sighted and blind participants in two auditory experiments designed to target different strategies for analyzing sounds: one experiment relied on the availability of local features at specific time points; the other one benefitted from global statistical averaging over longer durations. Three groups of participants were recruited: sighted controls (SC), congenitally blind (CB), and late-onset blind (LB) individuals. SC performed as expected: when sound duration increased, local analysis gave way to global analysis. CB individuals showed almost identical patterns of behavior, revealing that auditory processing of local features, as well as statistical averaging of those features, are not altered by the complete absence of vision since birth. Surprisingly, we found that interactions between auditory computations and

sight emerge later in development: LB individuals performed more poorly than those who were blind since birth. Crucially, performance was selectively degraded only for the use of local features, with no impact on statistical averaging.

Taken together, these results suggested that early development is characterized by a segregation between basic auditory computations and sight, while at later developmental phases a functional interplay between the access to local auditory details and availability of visual input is involved. This interaction appears to be highly selective, as it does not affect other aspects of auditory processing, such as temporal averaging of sound statistics.

INTRODUCTION

The auditory system is characterized by the capture of fine-grained details of sound waves (Plomp, 1964). These local temporal features are then integrated over time by mechanisms that retain, summarize, and abstract them into more compact acoustic percepts (Yabe *et al.*, 1998; McDermott, Schemitsch and Simoncelli, 2013). Computational synthesis approaches, derived by information theories (Barlow, 1961), allow to investigate these processes by implementing mathematical models to describe the set of measurements that the auditory system operates (McDermott and Simoncelli, 2011; McDermott, Schemitsch and Simoncelli, 2013). Such models have revealed that sounds are analyzed through the extraction of a set of auditory statistics (McDermott and Simoncelli, 2011) the processing of which represents the keystone of auditory features integration. Auditory statistics result from a set of computations strictly dependent on anatomical and functional properties of the auditory pathway (Ruggero, 1992; Dau, Kollmeier and Kohlrausch, 1997; Gygi, Kidd and Watson, 2004; Joris, Schreiner and Rees, 2004; Baumann *et al.*, 2011). Thus, they can be described only by biologically plausible models (McDermott and Simoncelli, 2011). The auditory system processes these statistics by averaging short-term acoustic events (McDermott and Simoncelli, 2011; McDermott, Schemitsch and Simoncelli, 2013; McWalter and McDermott, 2018), along specific time-windows (McWalter and McDermott, 2018) and uses this information to derive compact representations of sound objects.

While auditory statistics represent unimodal computations, the auditory system does not develop and function in isolation, and other senses, such as vision, modulate its functional and structural organization. For instance, studies in non-human animal model have revealed that in the early development, the onset of visual input gates the critical period closure of basic auditory functions (Mowery, Kotak and Sanes, 2016). Studies in humans have also suggested that visual inputs availability since birth might be a prerequisite for the full development of

specific auditory functions (e.g., auditory spatial calibration is impaired in congenitally blinds (Gori *et al.*, 2014). On the other hand, the lack of vision is known inducing compensatory effects in hearing. Consistent evidence exists that congenitally blind individuals outperform their sighted counterpart in a number of auditory tasks (for review see Pavani & Röder, 2012). Compensatory mechanisms have also been described for those individuals who have lost sight later in development (e.g., Fieger et al., 2006; Föcker et al., 2015; Röder & Rösler, 2003). However, none of these studies investigated the subtending auditory computations.

Whether auditory statistics develop and function exclusively within the influence of the auditory systems or whether they are influenced by other sensory modalities is as yet unknown. This study implemented a rigorous approach which allows to uncover auditory statistics computations from behavioral performances. Auditory statistics processing can be broken down into two main modes of representation: (1) the local features processing, by which fine-grained temporal details are extracted from a sound and stored; (2) the statistical averaging, the process by which local features are averaged within an integration time-window when the amount of information exceeds memory span and local details can no longer be retained (McDermott, Schemitsch and Simoncelli, 2013).

By testing blind populations against sighted individuals in two experiments designed to tap into these computational modes, we aimed at addressing whether they are influenced by visual input availability. Importantly, comparing populations that were visually deprived from birth or in late phases of the development allowed to assess whether there was a specific timing along the development within which visually driven alterations of auditory statistical processing can emerge. In other words, whether basic auditory computations and sight interact in early development or not. This represented a crucial dimension as early and late-onset adaptations to sensory deprivation seem to result from different neural mechanisms (Voss *et al.*, 2008; De Villers-Sidani and Merzenich, 2011; Collignon *et al.*, 2013; Castaldi, Lunghi and Morrone, 2020).

RESULTS

To understand whether and how visual experience affects the auditory statistics processing, we combined the study of human models of permanent visual deprivation with a computational approach. We took advantage of an already corroborated methodological pipeline (McDermott, Schemitsch and Simoncelli, 2013) and we produced different synthetic textures built upon original recordings. Thanks to their properties, a specific category of natural sounds, namely Sound Textures, was used (some examples are the rain, fire, bulldozer, typewriting,

waterfall sounds; (McDermott & Simoncelli, 2011; Saint-Arnaud & Popat, 2006; Schwarz, 2011). These sounds are rich, ubiquitous, and constant over time (McDermott, Schemitsch and Simoncelli, 2013; McWalter and McDermott, 2018). We selected 54 environmental recordings of Sound Textures (**Table S1**), among the original set implemented by McDermott, Schemitsch, and Simoncelli, 2013 (McDermott, Schemitsch and Simoncelli, 2013). Synthetic stimuli were created by using an Auditory Texture Model (McDermott and Simoncelli, 2011), which efficiently simulate computations performed at peripheral stages of the auditory processing. By computing time-averages of non-linear functions, it was possible to measure a set of statistics: envelope marginal moments, reflecting distribution and sparsity of the signal (Lorenzi *et al.*, 1999), envelope cross-correlation between cochlear envelopes, accounting for the presence of broadband events within the signal (McDermott and Simoncelli, 2011), modulation bands power, providing information about the temporal structure within cochlear channels (Bacon and Wesley Grantham, 1989; Dau, Kollmeier and Kohlrausch, 1997; McDermott and Simoncelli, 2011), and their correlations (McDermott and Simoncelli, 2011). Although the model represents a mathematical approximation, cochlear envelope statistics (marginal moments and pairwise correlations) are able to convey most of the perceptually relevant information about the sound (Smith, Delgutte and Oxenham, 2002; Gygi, Kidd and Watson, 2004; McDermott and Simoncelli, 2011). In fact, by generating sounds matching these statistics alone, it is already possible to obtain compelling Exemplars of the same original Sound Texture (McDermott and Simoncelli, 2011). By adding the remaining statistics, it is possible to obtain even more compelling results (McDermott and Simoncelli, 2011). Our experimental stimuli were created accordingly: by imposing all the aforementioned statistics on four different white noise samples, we synthesized, for each original Sound Texture, four different Exemplars of the original sound. Among themselves, Synthetic Exemplars of the same texture varied only for their local features, while their long-term average statistics matched the sound they were derived from. In other terms, this process resulted in four synthetic sounds which properties were constrained only by the selected average statistics extracted from the original recording **(Figure 1A)**. This provided us with the unique opportunity to test for specific aspects of the auditory statistics processing, thanks to the unparalleled level of control exerted over the statistics present in the synthesized sounds (for details about synthesis procedure, see Supplementary Material).

First, to address which specific aspects within the auditory statistic processing undergo crossmodal visual influence, we compared sighted and blind participants' performances in two selected experiments designed to exploit the two modes of auditory statistics representation.

Second, to assess whether the interplay between visual input availability and the two computational modes changes along the life cycle, we selected blind participants according to blindness onset, being it from birth or developmentally later (>10 years old; see **Table S2).** Thus, three groups of participants were recruited: congenitally blinds (CB), late-onset blinds (LB), and sighted controls (SC). All three groups were matched by size, age, and gender.

Both experiments consisted of a 2AFC oddity; participants had to detect the deviant sound among three acoustic samples, selecting between first and third interval. Stimuli were created by cutting each synthetic exemplar into smaller excerpts of different lengths. Each trial included three excerpts of the same length. Duration of the excerpts varied across trials, for a total of six durations (McDermott, Schemitsch and Simoncelli, 2013).

In the first experiment, Exemplar Discrimination, all three synthetic sounds were derived from the same original recording: two excerpts were exactly the same sound, while the odd one was an excerpt extracted from a different Synthetic Exemplar of the same Sound Texture. Participants were asked to report which sound (the first or the third) was different from the other two. **(Figure 1B).**

In the second experiment, Texture Discrimination, two excerpts were extracted from two distinct Synthetic Exemplars of the same Sound Texture (e.g., bulldozer), while the deviant one was drawn from a Synthetic Exemplar derived from a different Sound Texture (e.g., waterfall). Participants were asked to report which sound (the first or the third) came from a different acoustic source (**Figure 1C)**.

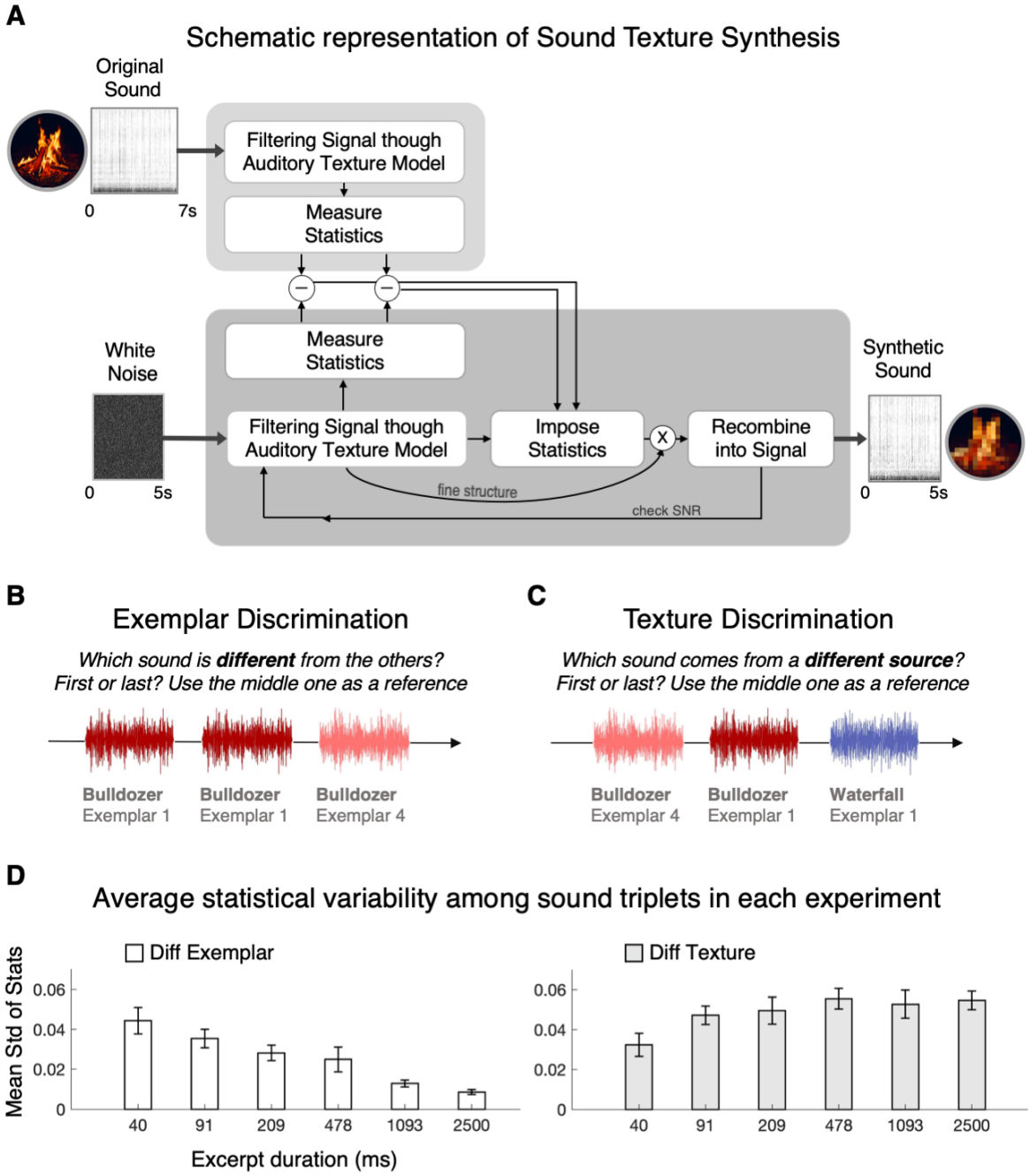

Figure 1. Sound Texture Synthesis, Auditory Statistics Variability, and Experimental Design
(A) Schematic representation of the Sound Texture Synthesis procedure employed to produce synthetic stimuli. A 7-s Original Recording was passed through the Auditory Texture Model [5] to extract average statistics of interest. A white noise sample was then passed again through the model while the Original Recording statistics were imposed on its cochlear envelopes. Modified envelopes were multiplied by their associated fine structure and recombined into the signal. This procedure was iterated until a desirable signal-to-noise-ratio is reached. The outcome was a Synthetic Sound Texture Exemplar, a 5-s signal containing statistics that match the original values and that was only constraint by them. Adapted from McDermott and Simoncelli, 2011.
(B) Exemplar Discrimination. Schematic representation of one trial. Participants had to detect the different sound among three, being the other two identical. In this case, the correct answer is the last sound since it is another exemplar of the "Bulldozer" Sound Texture.

(C) Texture Discrimination. Schematic representation of one trial. Participants had to report which sound was coming from a different source with respect to the other two. In this example, the correct answer is the third sound, being it an excerpt of a different Sound Texture
(D) Average variability across a set of statistics (envelope mean, skewness, variance, cross-correlation and modulation power) was computed from couples of excerpts, to measure, in both experiments, the objective statistical difference between reference and deviant sounds. Left: average standard deviation (std) across statistics measured in excerpts pairs originated from Different Exemplars of the same Sound Texture (for all textures in column 1, Table S1). When duration increased average statistics converged to the imposed original values and variability progressively tended to zero, increasing discrimination difficulty in Exemplar Discrimination. Right: average std across statistics measured in excerpts pairs derived from Different Sound Textures (column 1 and 2, Table S1). In Texture Discrimination, both scenarios (Different Exemplar and Different Texture) were presented and compared against each other. As duration increased, the difference between the two contexts increased, facilitating the recognition of the deviant one.
(See also Figure S3 and Table S1)

The employment of these experiments allowed to make specific predictions on the outcomes. Consistently with previous findings by McDermott, Schemitsch, and Simoncelli, 2013, opposite patterns of results were expected in the two experiments, as a function of excerpts duration. In Exemplar Discrimination, two sounds were identical, thus their reciprocal variability was zero. Optimal performance could occur when comparing the middle sound (reference) with the deviant sound, their average statistics variability clearly diverged from zero. For short stimuli, statistics were more dependent on the specific local features comprised in the segments thus their variability was higher. On the other hand, as stimuli duration increased, average statistics tended to converge towards original imposed values, thus for long excerpts variability progressively approached zero, making the sounds in the triplet perceptually more similar (**Figure 1D, Left panel**) and challenging task performance. Relying on local features was the optimal strategy to sustain the performance in this specific experiment across all durations, but since temporal information is not expected to be retained following statistical averaging (McDermott, Schemitsch and Simoncelli, 2013), as duration increased participants were expected to perform worse.

In Texture Discrimination, all three sounds in the triplets diverged for their local features. Two excerpts originated from different Exemplars of the same Sound Texture while the deviant sound was derived from another Sound Texture and comprised both different local features and imposed statistics. Since all three sounds represented different excerpts, the variability between couples was never zero, but the one between the two sounds originated from the same Texture tended to progressively decrease with duration, allowing for the deviant one to

remain the only markedly variable element in the triplet and to perceptually emerge (**Figure 1D, Right panel**).

In summary, for short stimuli, due to differences in feature variability among the three sounds, good performance was expected in Exemplar Discrimination as compared to Texture Discrimination, while for long stimuli statistical averaging was expected to boost performance in Texture Discrimination and hamper it in Exemplar Discrimination (McDermott, Schemitsch and Simoncelli, 2013), Any significant deviation from these expected outcomes would indicate changes in the processing of local features and/or statistical averaging.

The attended pattern of results (McDermott, Schemitsch and Simoncelli, 2013) was confirmed in our SC group. Performance was better for short durations (40, 91ms) in Exemplar Discrimination as compared to Texture Discrimination (all $p < 0.003$, corrected). Conversely, for long durations (478, 1093, 2500ms) participants' accuracy was higher in Texture Discrimination as compared to Exemplar Discrimination (all $p < 0.03$, corrected). No difference was observed for trials comprising stimuli that were 209ms long ($p = 0.31$, corrected; see **Figure 2A).** Overall, the data replicated previous findings in sighted controls, despite participants being blindfolded. Thus, these results represent a validated context to assess whether visual experience impacts on auditory statistics processing.

The CB group displayed a remarkably similar pattern of results. Better performance was found in Exemplar Discrimination for short durations (40, 91ms) compared to Texture Discrimination (all $p < 0.02$, corrected), and, conversely for long durations (478, 1093, 2500ms) in Texture Discrimination compared to Exemplar (all $p < 0.006$, corrected). As observed in SC, there was no difference between the two experiments for stimuli that were 209ms long ($p = 0.86$, corrected; see **Figure 2B).**

By contrast, in LB group no significant differences were found between the performance in Exemplar Discrimination and in Texture Discrimination for all short stimuli (40, 91, 209ms; all $p > 0.05$, corrected)**.** However, for long durations (478, 1093, 2500ms), LB participants performed better in Texture Discrimination as compared to Exemplar Discrimination (all adjusted $p < 0.001$), in line with what was observed in the other groups (**Figure 2C**).

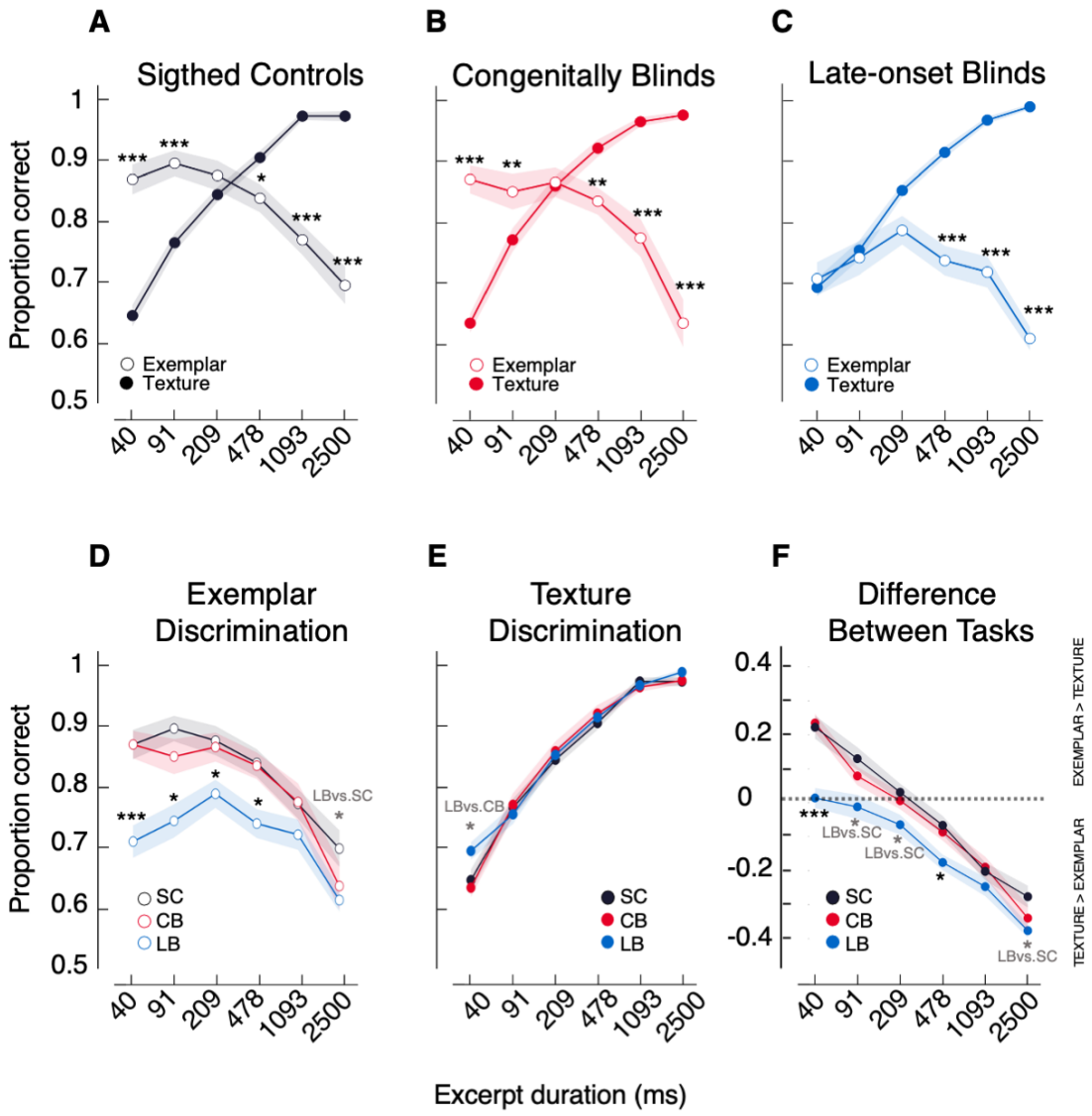

Figure 2. Proportion of correct answers in the two Experiments
(A, B, C) Results for Exemplar Discrimination vs. Texture Discrimination in each group. Proportion of correct answers across individuals at the group level are shown as a function of excerpt duration.
(D) Between Group comparisons in Exemplar Discrimination. SC and CB groups' performance did not differ. LB group showed an impaired performance as compared to the other groups: late sight loss has a detrimental impact when performance could benefit from higher local features variability.
(E) Between Group comparisons in Texture Discrimination. No significant differences were observed between SC and CB groups. LB performed better for 40ms stimuli compared to CB.
(F) Relative difference between experiments for all three groups. For each group and duration, the averages across participants of the differences between the performance in the two tasks are displayed. Positive values are found when performance in Exemplar is better than in Texture Discrimination, while negative values represent better performance in Texture compared to Exemplar Discrimination. Differently from the other two groups, LB never showed an advantage in Exemplar Discrimination compared to Texture Discrimination.
Shaded regions show interpolated standard error of the mean (SE) at each point. Results were corrected for multiple comparisons using the false discovery rate (FDR). If more than one comparison was significant, stars refer to the lower bound; gray stars indicate that only the labeled comparisons were significant; *** p<.001; ** p<.01; * p<.05.
(See also Figure S2 and Figure S4).

Late-onset sight loss hampers the processing of sound local features

When contrasting the performance of SC group with the one of CB group, no significant difference could be detected for all durations (all $p > 0.29$, corrected). Results clearly revealed that the processing of temporal fine-grained details is resilient to the absence of visual input since birth.

Conversely, the LB group performance was impaired for almost all of the tested durations as compared to both SC group (40, 91, 209, 478, 2500ms; all $p < 0.03$, corrected) and CB group (40, 91, 209, 478ms; all $p < 0.001$, corrected).

Results suggested an altered capability of late blind participants to discriminate sounds when the most efficient strategy is to base performance on local features. These findings reveal that visual input in early phases of development is not a prerequisite to acquire the ability to discriminate sounds according to their local features although that this process is encumbered by late onset blindness (**Figure 2D).**

Visual deprivation does not impact on statistical averaging

By comparing the performances in Texture Discrimination among the three groups, it was possible to directly address the impact of visual experience on statistical averaging efficiency.

The performance of the SC group for any of the selected duration (40, 91, 209, 478, 1093, 2500ms) did not differ from both the CB group (all $p > 0.47$, corrected) and the LB group (all $p > 0.06$, corrected). When comparing the accuracy of the CB group with the one of LB group, LB performed better for trials where stimuli were 40ms long (adjusted $p = 0.01$). No other difference was observed for all the remaining durations (91, 209, 478, 1093, 2500ms; all $p > 0.09$, corrected; **Figure 2E).** All together, these results reveal that visual deprivation does not exert a significant influence on the process by which auditory statistics are computed over time and used to identify different sound sources.

Relative difference between experiments reveal no advantages for LB when local features should support the performance

For each participant the accuracy scores in Texture Discrimination were subtracted from the ones in Exemplar Discrimination, separately for each duration, to compute the relative mean

difference between Experiments (Figure 2F). Results showed that compared to both SC and CB groups, in LB group this difference was significantly smaller for very short durations (LC vs. SC: 40, 91; all $p < 0.02$, corrected; LC vs. CB: 40 $p < 0.001$, corrected, 91 $p = 0.04$, uncorrected) and larger for longer ones (LC vs. SC: 209, 478, 2500; all $p < 0.03$, corrected; LC vs. CB: 478 $p < 0.03$, corrected; see Figure 2F; Table S3). Conversely, the relative difference of performance in the two Experiments between CB and SC did not differ for any of the durations (all $p > 0.32$, corrected; Figure 2F)

These results showed that both CB and SC were performing according to predictions showing specific advantages in one experiment or the other according to stimulus duration. On the contrary, LB group did not display a boost for those conditions in Exemplar Discrimination in which local feature processing could have helped the performance.

Ruling out possible confounds

It could be argued that results in LB group were idiosyncratic of the participants included in the study. However, sample size was adequate (N = 18 per group) and relatively large compared to previous investigations on blind individuals; all groups were properly matched by several main variables (size, age, and gender), and all participants had no documented auditory deficits, cognitive impairments, or neurological disorders (blindness was associated only to peripheral damage; **Table S1**; See Supplementary Material). Moreover, LB participants' performance was hampered only in one of the two experiments, while the observed results in Texture Discrimination were indistinguishable from the ones of the remaining groups, for most of the selected durations. If anything, LB group performance was significantly more efficient at 40ms as compared to CB and partially SC ($p < 0.04$, uncorrected). In light of these observations, it was possible to exclude that a general cognitive or acoustic impairment could explain the lack of advantage specific for Exemplar Discrimination.

In order to rule out other possible confounds, we ran specific tests on our sample data. Providing the temporal presentation of triplets in the employed 2AFC protocol, it could have been possible that a specific disposition bias towards the first or last interval was present and diverged among groups, at least partially accounting for different results. This was not the case, as all groups did not significantly differ in terms of predisposition towards stimulus intervals (see Supplementary Material; **Figure S4A**).

Another possible confounding effect could have been a between group difference associated to learning and/or tiredness within an experimental session. It could have been possible that

LB group performance had changed as experiment proceeded (e.g. progressively diminishing across runs, specifically in the Exemplar Discrimination). However, this was not the case. Comparing accuracy across runs, a similar trend across all groups emerged for each duration (see Supplementary Material; **Figure S4B**).

In light of these clarifications, results can genuinely be attributed to late-onset sight loss hampering the use of local features

DISCUSSION

The present study aimed at addressing whether visual experience at different phases of the life span exerts a crossmodal influence over specific auditory statistics computations. No difference was observed between CB and SC groups for both modes of representation. Conversely, we found that LB performance was selectively impaired with respect to both SC and CB, for those conditions in which optimal performance relied on local features. Taken together, these results provided evidence that the lack of vision can have a negative impact on specific peripheral computations but only when visual input was available during early developmental phases and went missing afterwards.

Auditory statistics processing develops regardless of visual input availability

Blindness represents a natural state in which it is possible to address crossmodal interdependencies of sensory functions. By comparing CB with SC, our study investigated whether visual input was necessary for the typical development of the two auditory modes of representation underlying the auditory statistics processing, and on the other side, whether compensatory mechanisms emerged due to lack of vision since birth. Therefore, two different outcomes could have been expected.

First, if visual experiences were necessary to properly develop the ability to process local features and/or to compute average statistics, we could have observed an impaired performance of CB in one of the two experiments, or both. For example, evidence exists that CB fail at performing auditory space bisection tasks (Gori *et al.*, 2014), and this observation provides evidence that visual experience is necessary to efficiently encode Euclidian coordinates of sounds (Gori *et al.*, 2014; Gori, Amadeo and Campus, 2020b, 2020a). Second, coherently with previous evidence of enhanced auditory skills in congenitally and early blinds (e.g. Doucet et al., 2005; Muchnik et al., 1991; Röder et al., 1999), lack of vision since birth could have improved the sensitivity to the auditory information included in sound textures, leading to the emergence of specific compensatory mechanisms. For instance, scattered

evidence suggests that blind individuals are able to understand syllables at a greater time speed compared to natural speech (Moos and Trouvain, 2007; Trouvain, 2007; Dietrich, Hertrich and Ackermann, 2013), an ability perhaps supported by a higher auditory sampling rate capacity. Thus, we could have expected that CB were able to retain more local features in time before averaging statistics, showing better performance for long durations in Exemplar Discrimination. On the other hand, a compensatory mechanism favoring the statistical averaging mode would have led to better results in Texture Discrimination. Furthermore, a better frequency tuning [(Huber *et al.*, 2019)] to temporal local features in CB would have enhanced the sensitivity to small acoustic differences, leading to better performances for short excerpts both in Exemplar and Texture Discrimination. However, none of these hypotheses was confirmed in our data, as CB performance was indistinguishable from the one of SC. Thus, our results strongly suggest a relative independence of the auditory statistic processing from early visual experience and no need for compensatory mechanisms to arise due to the lack of vision since birth.

Previous evidence already suggested the existence of auditory functions which develop independently from visual experience since birth (for instance, auditory gap detection threshold (Weaver and Stevens, 2006), pure tone threshold audiometry, and acoustic reflex threshold (Starlinger and Niemeyer, 1981); for functions in the tactile domain see also (Barolo, Masini and Antonietti, 1990; Röder, Spence and Rösler, 2000). Similarly, it seems that the development of auditory computations tested in this study is not influenced by other senses availability.

We can argue that the extraction of the auditory statistics necessary for textures recognition occurs at a very basic level of processing, while functions that showed visual input dependencies are mostly the result of higher order operations at the sensory cortex level. Evidence suggests that multisensory functions performed at subcortical levels seem to exist from early developmental stages (Lewkowicz, 2000), and thus, they rely less on experience compared to cortical multisensory functions (e.g. Putzar et al., 2010). As the auditory model used in our study to extract and impose statistics represented peripheral computations, from the cochlea up to the midbrain (McDermott and Simoncelli, 2011), it is possible that the typical development of the auditory statistics processing of Sound Textures is less experience-dependent from visual inputs than other high-level cortical computations underpinning previously documented behavioral adaptations. Further studies are required to resolve this open-ended issue, including statistics resulting from higher-order computations (Chi, Ru and Shamma, 2005; Norman-Haignere and McDermott, 2018) and involving other types of naturalistic stimuli.

Functional interplay between auditory details processing and sight along the development

By comparing CB, SC, and LB groups we can affirm that while early vision is not necessary for the typical development of the auditory statistics processing, visual experience can still exert an influence.

A lack of associations between the accuracy in both tasks and duration or onset of blindness was found and (see Supplementary Material; **Figure S5**) suggested that the performance was not influenced by the number of years people were visually deprived (in our LB sample, duration of blindness spanned from 2 years up to 28 years) and was similar for people who became blind during childhood (10 years of age) as well as during adulthood (up to 51 years of age, in our LB sample). However, we had the chance to test two early blind individuals, whose blindness onset occurred during their third year of life (See Supplementary Material, **Figure S1**). Remarkably, their results systematically overlapped with the ones of CB and SC, providing evidence that the dampening of local features processing manifests only if sight loss occurs rather late in the development.

Together with main results, these observations introduce an intriguing open-ended issue regarding the fact that sight loss was able to exert an influence only at late developmental stages. One possibility is that a visual influence on auditory computations can only take place after the complete development of the auditory systems has occurred. Consistent evidence suggests that even considering basic auditory processing, human performance improves gradually over nearly a decade. Frequency discriminations, such as perceiving a difference between two tones presented sequentially, does not mature until roughly 10 years of age for low frequencies (Maxon and Hochberg, 1982; Jensen and Neff, 1993; Moore *et al.*, 2011). Similarly, amplitude modulation detection thresholds become adult-like only after 10 years of age (Banai, Sabin and Wright, 2011). In accordance with these observations, after 10 years of age, plasticity of both peripheral and central auditory systems is greatly reduced (Sharma, Dorman and Spahr, 2002). The use of local features comprised a number of operations, including the measurement of amplitude modulations over time (Dau, Kollmeier and Kohlrausch, 1997). Thus, it is possible they are designed to develop independently from visual input and only after their functional development is completed interactions across senses are allowed. This would account for the effect of sight loss becoming explicit only at a rather late developmental stage.

Alternatively, it is possible that the observed effects depend on the development of multisensory functions. Previous studies have revealed that certain aspects of multisensory

integration can occur only by the age of 8-10 years (Gori *et al.*, 2008). On the same vein, basic audio-visual (AV) multisensory facilitations have been found immature until the age of 9 years old while similar patterns have been observed between adolescents and adults (Brandwein *et al.*, 2011). Similarly, also the development of multisensory speech perception has been found to progress until late childhood (Ross *et al.*, 2011). The present data might suggest that the interactions between basic auditory computations tested here and vision occurs only after full development of AV multisensory functions. The availability of visual input in early developmental phases would prompt the typical development of AV interactions. As a result, the sudden loss of visual input could in turn alter auditory processing which have typically developed.

Future investigations should frame the developmental trajectory of the interactions between these auditory computations and sight, for example by testing other participants who became blind within 3 and 10 years of age, to estimate the shape function across life cycles and the different experience-dependent neural mechanisms involved.

Functional interplay between selective auditory computations and vision

Which reason can we suggest for local features processing being selectively impaired, despite unaltered statistical averaging? To answer this question, we need to consider that local features processing must involve different steps, specifically features encoding integration over time, and retention (McDermott, Schemitsch and Simoncelli, 2013). As statistics are averages of temporal features over time (McDermott and Simoncelli, 2011; McDermott, Schemitsch and Simoncelli, 2013), basic encoding of local features is fundamental in order for statistical averaging to emerge. Participants in the LB group did not show any impairment in Texture Discrimination, thus they appeared to be capable to encode features and compute averages out of them. On the other hand, results for all groups in Exemplar Discrimination showed that as the system proceeds to integrate features over time, their retention goes missing due to storage capacity limitations (see also McDermott et al., 2013). Thus, we can postulate that statistical averaging could in principle occur normally, despite the temporal dynamics of local details integration and/or retention being altered. Specifically, two hypotheses can be proposed. First, it is possible that LB individuals started to discriminate sounds only once consistent amount of information was provided. In other words, the deficit observed in Exemplar Discrimination for short intervals (< 500ms) could reflect changes in the temporal window of features integration. Second, we could assume that, for LB participants, local features became unavailable earlier as compared to the other groups. Thus, the deficit observed in our sample could be specific for the retention of local features, which for brief

intervals went lost for LB and not for the other two groups. Further investigations, focused on breaking down the process into its subcomponents and tackling them separately, are required to disentangle which aspect within the local features processing is specifically altered after late-sight loss. This will allow to further understand interdependencies across modalities of subtle auditory computations and to track their developmental trajectory in a multimodal framework.

Noticeably, the deficit observed in the LB group does not exclude that limiting local features accessibility can provide ecological advantages. Identifying a Sound Texture often equal to recognize the statistics included in its sound waveform (McDermott and Simoncelli, 2011). Thus, it is possible that relying on statical averaging only when information is consistent and/or at the expense of temporal details prompts sound-object recognition in everyday environment. Adult perceptual learning (Fiorentini & Berardi, 1997; Watanabe and Sasaki, 2015) has often been associated to the remapping of sensory cortex (Gilbert, Sigman and Crist, 2001; Li, Piëch and Gilbert, 2004), is driven by feedback regulations (Schäfer, Vasilaki and Senn, 2007; Gilbert, Li and Piech, 2009), and does not reflect only exposure to sensory inputs, but the salience of stimulus and task to fulfill ecological purposes. (Polley, Steinberg and Merzenich, 2006). The results in our LB group could suggest a form of adaptive perceptual learning relying on the implementation of strategical changes to face a remarkable loss in the overall available sensory input.

Possible effects on other modalities

This study showed that combining different computational methods with human models of sensory deprivation can provide a valid context to assess plasticity changes in specific operations performed by the sensory systems, even at peripherical levels of processing. However, it is not clear whether this effect could be specific for auditory system alone or if computations within different senses could be affected in a similar way, especially providing the resemblance of the Auditory Texture Model (McDermott and Simoncelli, 2011) implemented in this study with a previously used Visual Texture Model (Portilla and Simoncelli, 2000), and the presence of Textures in other modalities, such as touch (Picard *et al.*, 2003; Weber *et al.*, 2013).

CONCLUSION

Overall, results suggest that early visual inputs are not required for the full development of the network sustaining the auditory statistics processing. Typical development of these processes might principally rely on the interaction of intrinsic biological properties of the auditory system

with the exposure to statistics included in sounds. However, even if crossmodal visual influence on auditory statistics processing is not explicit in early development, it becomes so when the sight goes missing at later developmental stages, leading to selective impairments. This study has important implications, not only because it shows a form of crossmodal re-adaptation that could not otherwise be tested, but also in terms of different auditory rehabilitation strategies to be implemented for those people who lost vision compared to those people who were born blind.

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Author Contributions

Conceptualization, D.B and M.B; Methodology, M.B. and D.B.; Investigation M.B. and D.B.; Writing – Original Draft, M.B. and D.B.; Writing – Review & Editing, M.B, D.B.; Visualization, M.B. and D.B.; Funding D.B (PRIN 2017 research grant. Prot. 20177894ZH).

Declaration of Interests

The authors declare no competing interests.

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