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Speech understanding with bimodal stimulation is determined by monaural signal-to-noise ratios – no binaural cue processing involved

Benjamin Dieudonné, Tom Francart

Experimental Oto-rhino-laryngology, Department of Neurosciences, KU Leuven – University of Leuven, Belgium.

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Address correspondence to:

Tom Francart, Experimental Oto-rhino-laryngology, Department of Neurosciences, KU Leuven – University of Leuven, Herestraat 49 bus 721, 3000 Leuven, Belgium.

E-mail: tom.francart@med.kuleuven.be, benjamin.dieudonne@med.kuleuven.be

Abstract

Objectives: To investigate the mechanisms behind binaural and spatial effects in speech understanding for bimodal cochlear implant listeners. In particular, to test our hypothesis that their speech understanding can be characterized by means of monaural signal-to-noise ratios, rather than complex binaural cue processing such as binaural unmasking.

Design: We applied a semantic framework to characterize binaural and spatial effects in speech understanding on an extensive selection of the literature on bimodal listeners. In addition, we performed two experiments in which we measured speech understanding in different masker types (1) using head-related transfer functions, and (2) while adapting the broadband signal-to-noise ratios in both ears independently. We simulated bimodal hearing with a vocoder in one ear (the cochlear implant side) and a low pass filter in the other ear (the hearing aid side). By design, the cochlear implant side was the main contributor to speech understanding in our simulation.

Results: We found that spatial release from masking can be explained as a simple trade-off between a monaural change in signal-to-noise at the cochlear implant side (quantified as the head shadow effect) and an opposite change in signal-to-noise at the hearing aid side (quantified as a change in bimodal benefit). In simulated bimodal listeners, we found that for every 1 dB increase in signal-to-noise ratio at the hearing aid side, the bimodal benefit improved by approximately 0.4 dB in signal-to-noise ratio.

Conclusions: Although complex binaural cue processing is often implicated when discussing speech intelligibility in adverse listening conditions, performance can simply be explained based on monaural signal-to-noise ratios for bimodal listeners.

Keywords: cochlear implants; hearing aids; bimodal cochlear implant listeners; speech intelligibility; binaural hearing; spatial release from masking; head shadow; binaural intelligibility level difference; binaural squelch; binaural redundancy; binaural contrast; binaural interaction; interaural time differences; interaural level differences; binaural information; binaural cues

I. Introduction

An increasing number of cochlear implant (CI) users have residual hearing in the non-implanted ear. Even when the non-implanted ear is too impaired for proper speech understanding, it is often supplied with a regular hearing aid. This contralateral hearing aid results in the so-called bimodal benefit: a benefit of listening with both CI and hearing aid as compared to listening with the CI only. The bimodal benefit manifests itself as improved localization ability (or at least some spatial awareness) and improved speech intelligibility (Ching et al., 2004, 2007; Francart & McDermott, 2013; Van Hoesel, 2012).

The improved spatial awareness is due to the perception of binaural cues (mostly interaural level differences); note that performance widely varies across bimodal listeners, and great efforts are being made to improve their perception of binaural cues (Dieudonné & Francart, 2018a; Francart et al., 2011, 2014; Hu et al., 2018; Veugen, et al., 2016b).

The improved speech understanding is mostly attributed to complementarity: the hearing aid supplies information that is not supplied by the CI, such as the temporal fine structure of sound. Moreover, the perception of binaural cues might give bimodal listeners the opportunity of *binaural unmasking*, although this is a topic of debate (Van Hoesel, 2012).

In this paper, we argue that binaural cues do not contribute to speech understanding in bimodal listeners. In other words, we argue that bimodal listeners do not experience binaural unmasking. First, we explain our methodology to investigate the separate benefits of binaural hearing in speech understanding, based on a semantic framework that we recently developed (**sections I.A** and **I.B**). Second, we apply this framework on an extensive selection of the literature on speech understanding in bimodal listeners, to support our hypothesis that there is no evidence for binaural cue processing, and that bimodal benefit might be a simple function of the signal-to-noise ratio in the hearing aid (**section I.C**). Third, and finally, we perform two experiments with acoustic simulations of bimodal listening to further support our hypotheses. (**sections III** and **IV**).

A. Theoretical framework to disentangle binaural speech understanding in normal-hearing listeners

For normal-hearing listeners, the importance of binaural hearing to understand speech in complex listening environments has been well-established in the literature (e.g., Blauert, 1997). Binaural performance is often quantified (1) by comparing speech understanding in situations with spatially collocated speech and noise versus spatially separated speech and noise – what we call a *spatial benefit* –, or (2) by comparing speech understanding with one ear versus with two ears – what we call a *binaural benefit*. The effects can be measured quantitatively by comparing speech reception thresholds or percentage correct scores in speech understanding tasks. Recently, we established a semantic framework to unambiguously define and relate the resulting measures (for normal-hearing listeners), as depicted in **Figure 1** and explained below (Dieudonné & Francart, 2018b).

The vertical axis shows spatial benefits. *Spatial release from masking* (*SRM*) is the benefit in speech understanding of spatially separating target speech and masking noise (e.g., masker towards the right ear) while listening binaurally. *Head shadow* is the monaural contribution to SRM: the benefit in speech understanding due to the increase in signal-to-noise ratio (SNR) in one ear. *Binaural contrast* (also known as binaural interaction) is the binaural contribution to SRM: simply, the additional benefit in SRM that cannot be explained by head shadow, but is attributed to *binaural unmasking*; mathematically, the difference between SRM and head shadow:

$$\mathrm{BC} \triangleq \mathrm{SRM} - \mathrm{HS} \quad (1)$$

where BC is binaural contrast, SRM is spatial release from masking and HS is head shadow.

The horizontal axis represents binaural benefits, i.e., the benefit of listening with two ears instead of one*. *Redundancy* (also known as binaural summation) is the benefit of adding a second ear with

* When listening with two ears deteriorates speech understanding, instead of improving it, this is called *binaural interference*.

identical information. *Squelch* (also known as binaural intelligibility level difference) is the benefit of adding a second ear with inferior information: an ear with a lower SNR. The addition of this ear also supplies spatial information: interaural differences, also called binaural cues. To be certain that spatial information is used in squelch – and not only (inferior) redundant information – one should compare squelch with redundancy. The difference between squelch and redundancy is mathematically equivalent to the difference between SRM and head shadow within this framework (see also Dieudonné & Francart, 2018b), such that both definitions can be used to measure binaural contrast:

$$\mathrm{BC} = \mathrm{SQ} - \mathrm{RED} \qquad (2)$$

where BC is binaural contrast, SQ is squelch and RED is redundancy.

Note that both squelch and SRM are often unjustifiably measured to demonstrate binaural cue processing, while both of them involve a confounding component apart from binaural cue processing: when considering squelch, redundant information is also supplied; when considering SRM, a monaural increase in SNR is also involved. Formulae (1) and (2) isolate the component that corresponds to binaural processing of spatial cues, by subtracting the respective confounding component. As such, binaural contrast is the *only* measure within this framework that can demonstrate binaural cue processing.

To summarize, all above-mentioned spatial and binaural benefits are linked via the following equation, which can be obtained by combining equations (1) and (2) (or intuitively, by "following the arrows" in **Figure 1**):

$$\begin{aligned}\mathrm{SRM} &= \mathrm{HS} + \mathrm{SQ} - \mathrm{RED} \\ &= \mathrm{HS} + \mathrm{BC} \qquad (3)\end{aligned}$$

where SRM is spatial release from masking, HS is head shadow, SQ is squelch, RED is redundancy and BC is binaural contrast. As such, SRM is a simple sum of a monaural term – head shadow – and a binaural term – binaural contrast.

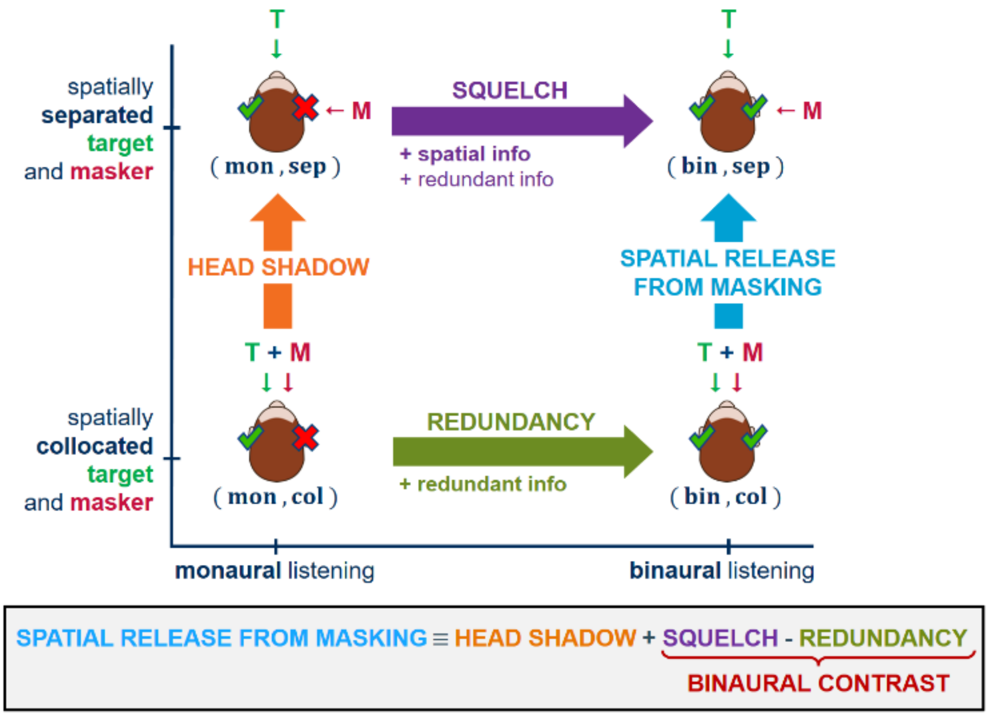

Figure 1: Semantic framework to define and relate the different effects involved in spatial release from masking (SRM) for normal-hearing listeners. Within this framework, SRM is the simple sum of a monaural term, head shadow, and a binaural term, binaural contrast. Binaural contrast is the trade-off between supplying spatial information (squelch) and supplying redundant information (redundancy); it represents a true benefit of binaural cue processing.

B. Translation of the framework towards bimodal listeners

The translation – and in particular interpretation of this framework – towards bimodal listeners is not trivial, since their hearing is strongly asymmetric: SRM is now different when noise is at the CI or hearing aid side, and monaural listening is different with the CI than with the hearing aid.

Therefore, there are now more listening conditions to take into account (9[†] instead of 4), such that extra care should be taken when discussing the binaural and spatial effects.

In asymmetric hearing, one could argue that there is one *dominant ear* – also referred to as better-hearing or better-performing ear (e.g., Gifford et al., 2014), i.e., the ear that contributes most to speech understanding – and one *complementary ear* – the ear that gives an extra benefit as compared to listening with only the dominant ear. For example, for a person with single-sided deafness and a CI in the deaf ear, the normal-hearing ear is most probably the dominant ear. Therefore, monaural listening is then usually measured as listening with the normal-hearing ear (e.g., Vermeire & Van de Heyning, 2009), to avoid that any measured "binaural benefit" is simply due to listening with the normal-hearing ear instead of with the CI. On the other hand, for many bimodal listeners, the residual hearing is often too poor for proper speech understanding, such that the implanted ear is the dominant ear[‡]. In this case, monaural listening is usually measured as listening with the CI only (e.g., Ching et al., 2004). Here, we consider the latter case, such that we do not consider listening with the hearing aid only. As such, we only have 6[§] listening conditions to take into account. The framework could easily be translated towards other asymmetric situations (such as single-sided deafness with a CI in the deaf ear), by reconsidering which ear is dominant.

We explain SRM for noise at the hearing aid or at the CI separately, as depicted in **Figure 2(a)** and **Figure 2(b)** respectively, and explained below. As with normal-hearing listeners, each effect can be measured quantitatively by comparing speech reception thresholds (as we do in this work, see **Table 2** in the **Methods** section of **Experiment 1**) or by comparing percentage correct scores in speech understanding tasks.

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† 3 device set-ups (only CI, only hearing aid, binaural) x 3 spatial set-ups (spatially collocated target and masker in front, masker spatially separated at CI side, masker spatially separated at hearing aid side) = 9 conditions.

‡ Note that this depends on the country and its implantation criteria. For example, in Belgium, speech intelligibility in quiet with a regular hearing aid cannot be better than 30% to be eligible for reimbursed implantation.

§ 2 device set-ups (only CI, binaural) x 3 spatial set-ups (spatially collocated target and masker in front, masker spatially separated at CI side, masker spatially separated at hearing aid side) = 6 conditions.

B. 1. Noise at the hearing aid side

When the noise is moved to the hearing aid side (**Figure 2(a)**), there is a monaural increase in SNR in the CI due to the *head shadow*, similar to the head shadow benefit for normal-hearing listeners (see **section I.A**). On the other hand, the *binaural benefits* (represented by the horizontal axis) are quite different for bimodal listeners, as they also include complementary information, next to redundant information and spatial information. Therefore, from a semantic standpoint, we prefer to abandon the terms squelch and redundancy in the bimodal case, as they cover more mechanisms than their names suggest. To avoid confusions about the binaural system, we will always refer to a *bimodal benefit* when adding the hearing aid as compared to listening with the CI only. We distinguish the different bimodal benefits by referring to the SNR at the hearing aid side relative to the CI side: *bimodal benefit with equal SNR at the hearing aid* ("redundancy") and *bimodal benefit with lower SNR at the hearing aid* ("squelch"). It is again important to note that neither of these benefits is necessarily the result of binaural cue processing (despite the fact that squelch is often claimed to be the result of binaural cue processing), as multiple mechanisms are involved in each bimodal benefit: the addition of complementary, redundant and spatial information (Van Hoesel, 2012). As with normal-hearing listeners, one can only investigate the binaural utility of spatial information by measuring *binaural contrast*, i.e., by subtracting the head shadow benefit from SRM, or equivalently, by subtracting the two bimodal benefits:

$$\begin{aligned} BC &= SRM_{HA} - HS(SNR_{CI}\uparrow) \\ &= BB(SNR_{HA} < SNR_{CI}) - BB(SNR_{HA} = SNR_{CI}) \\ &= \Delta BB(SNR_{HA}\downarrow) \end{aligned} \tag{4}$$

where BC is binaural contrast, SRM_{HA} is spatial release from masking for noise moved towards the hearing aid, HS is head shadow, BB is a bimodal benefit, and ΔBB is the difference between two bimodal benefits. If we rearrange equation (4), we obtain the following relationship to disentangle SRM_{HA}:

$$SRM_{HA} = HS(SNR_{CI}\uparrow) + BB(SNR_{HA} < SNR_{CI}) - BB(SNR_{HA} = SNR_{CI})$$

$$= HS(SNR_{CI}\uparrow) + \Delta BB(SNR_{HA}\downarrow)$$

$$= HS(SNR_{CI}\uparrow) + BC \quad (5)$$

As such, SRM_{HA} is also the sum of a monaural term – head shadow benefit due to increase of SNR at the CI – and a binaural term – a difference in bimodal benefit when SNR at the hearing aid decreases. If the latter term is positive, this implies a benefit of binaural cues, i.e., binaural unmasking. To our knowledge, binaural contrast has never been measured explicitly for bimodal listeners.

B. 2. Noise at the cochlear implant side

When the noise is moved to the CI side (**Figure 2(b)**), the translation of our framework is less straightforward. Now, there is a monaural *decrease in SNR* in the CI, which can be represented by a *head shadow disadvantage* (i.e., a negative head shadow benefit). The *binaural benefits* (represented by the horizontal axis) again include complementary, redundant and spatial information. They are again referred to as *bimodal benefits*, and distinguished by referring to the SNR at the hearing aid side relative to the CI side: *bimodal benefit with equal SNR at the hearing aid* ("redundancy") and *bimodal benefit with higher SNR at the hearing aid* (this one has no analogue in normal-hearing listeners[**]).

Again, neither of these bimodal benefits is necessarily the result of binaural cue processing due to the multiple mechanisms that are involved. Moreover, with the listening conditions that we consider here, it is *impossible* to investigate the binaural utility of spatial information, as we do not measure the benefit of monaural increase in SNR separately.[††]

[**] This measure is also used to quantify a head shadow benefit (Schafer et al., 2011). As with squelch, we prefer not to call it a head shadow benefit, due to the different mechanisms that are involved: providing an ear with better SNR as well as providing redundant and spatial information (Van Hoesel, 2012).

[††] Note that we choose to not measure a monaural head shadow benefit at the hearing aid, as many bimodal listeners cannot understand speech with the hearing aid only. In the case that a monaural head shadow benefit at the hearing aid can be measured, one could again measure binaural contrast by subtracting the head shadow benefit from SRM. As such, binaural contrast could be measured twice: once when the noise is moved towards the hearing aid side (as in I.B. 1), and once when the noise is moved towards the CI side.

SRM for noise moved towards the CI side can now be disentangled as follows:

$$SRM_{CI} = HS(SNR_{CI}\downarrow) + BB(SNR_{HA} > SNR_{CI}) - BB(SNR_{HA} = SNR_{CI})$$

$$= HS(SNR_{CI}\downarrow) + \Delta BB(SNR_{HA}\uparrow) \quad (6)$$

where SRM_{CI} is spatial release from masking for noise moved towards the CI side, HS is head shadow (here a disadvantage), BB is a bimodal benefit, and ΔBB is the difference between two bimodal benefits.

As such, SRM_{CI} is also the sum of a monaural term – head shadow disadvantage due to decrease of SNR at the CI – and a binaural term – a difference in bimodal benefit when the SNR at the hearing aid is increased. Note that the latter term is an advantage of providing spatial information *as well as extra complementary and redundant information*, and should therefore not be considered as binaural contrast. When monaural speech understanding cannot be measured with the hearing aid only (as is the case with very limited residual hearing), it is impossible within this framework to measure the sole advantage of providing spatial information when the noise is originating from the CI side.

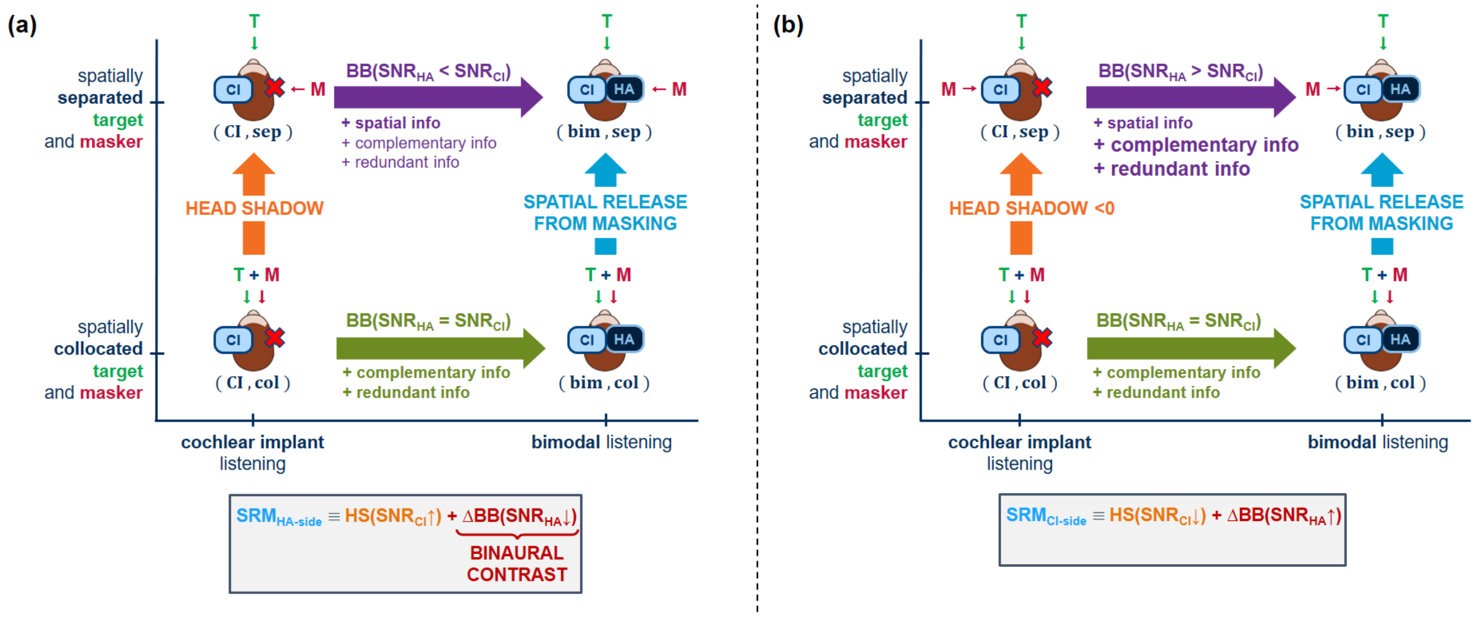

Figure 2: Semantic framework to define and relate the different effects involved in SRM for bimodal listeners. As bimodal listening is asymmetric, two separate cases of SRM should be considered. In both cases, we consider monaural listening as listening with only the CI (the *dominant* ear), as many bimodal listeners cannot understand speech with the hearing aid only (the *complementary* ear). The framework could easily be translated towards other asymmetric situations (such as single-sided deafness with a CI in the deaf ear), by reconsidering which ear is the dominant one.

(a) Noise moved towards the hearing aid side. This is the most straightforward translation of the framework for normal-hearing listeners (**Figure 1**). However, we choose to abandon the terms redundancy and squelch, and refer to both of them as a bimodal benefit. Here, binaural cue processing can again be measured as *binaural contrast*.

(b) Noise moved towards the CI side. This case is less straightforward, as the head shadow now results in a deterioration of SNR. In this case, binaural cue processing cannot be quantified with any of the defined measures.

C. Application of the framework on the literature: disentangling SRM in bimodal listeners

While all these effects (head shadow, redundancy, squelch, spatial release from masking, etc.) have been investigated extensively for normal-hearing listeners – and it is still an intensely debated topic, for a recent overview, see Dieudonné & Francart (2018b) – little research has been done to explicitly investigate which mechanisms mediate these effects in bimodal listeners. Mostly, the different measures have been quantified to compare their performance with other groups (e.g., normal-hearing listeners or bilateral CI listeners) (Schafer et al., 2007; 2011), or to compare performance between different signal processing strategies (Veugen et al., 2016a; Vroegop et al., 2018). Differences in performance are then explained from a direct translation of what is behind the effects in normal-hearing listeners, i.e., in terms of spatial attention, binaural cue processing, etc. Here, we apply our framework on an extensive selection of the literature, to conclude that there is no evidence for any binaural cue processing in speech understanding of bimodal listeners, as had been already suggested by Van Hoesel (2012), and to investigate how SRM can be explained instead. Schafer et al. (2011) conducted a systematic literature review of 42 peer-reviewed articles in which they compared head shadow, redundancy and squelch (corresponding with bimodal benefits for noise coming from the CI side, from front and from the hearing aid side respectively, according to our definitions) for bimodal listeners and bilateral CI listeners. Between-group differences in squelch were speculated to result from the effectiveness of the brain to suppress noise due to spatial separation – although it could equally well be different processing of complementary and/or redundant information. Since the review of Schafer et al. (2011), more researchers have investigated binaural advantages in bimodal listeners (Gifford et al., 2014; Kokkinakis & Pak, 2014; Morera et al., 2012; Pyschny et al., 2014); again, binaural cue processing was often suggested when squelch was measured. **Figure 3** summarizes the results from all above-mentioned (reviewed) studies in which the bimodal benefit was (or could be) calculated for different noise locations (Tyler et al., 2002; Morera et al., 2005; Dunn et al., 2005; Litovsky et al., 2006; Mok et al., 2006; Yuen et al., 2009; Mok et al., 2010; Morera et al., 2012; Gifford et al., 2014; Kokkinakis et al., 2014; Pyschny et al., 2014), and shows within-study differences in bimodal benefit ΔBB (which we calculated from the extracted bimodal benefits). It can be seen that there was no case in which binaural contrast was positive (except for one study by Morera et al. (2005) where binaural contrast equaled 3%, which is most likely not a significant result). Therefore, there is no strong evidence for binaural cue processing in speech understanding for bimodal listeners, i.e., no strong evidence for binaural unmasking. Moreover, bimodal benefit appears to be largest when adding an ear with better SNR ($BB(SNR_{HA} > SNR_{CI})$), smallest when adding an ear with lower SNR ($BB(SNR_{HA} < SNR_{CI}$), mostly reported as "squelch"), and somewhere in between when adding an ear with equal SNR ($BB(SNR_{HA} = SNR_{CI}$), mostly reported as "redundancy" or "summation"). This dependence of the bimodal benefit on the noise location suggests that the bimodal benefit might be a simple function of the signal-to-noise ratio at the hearing aid side.

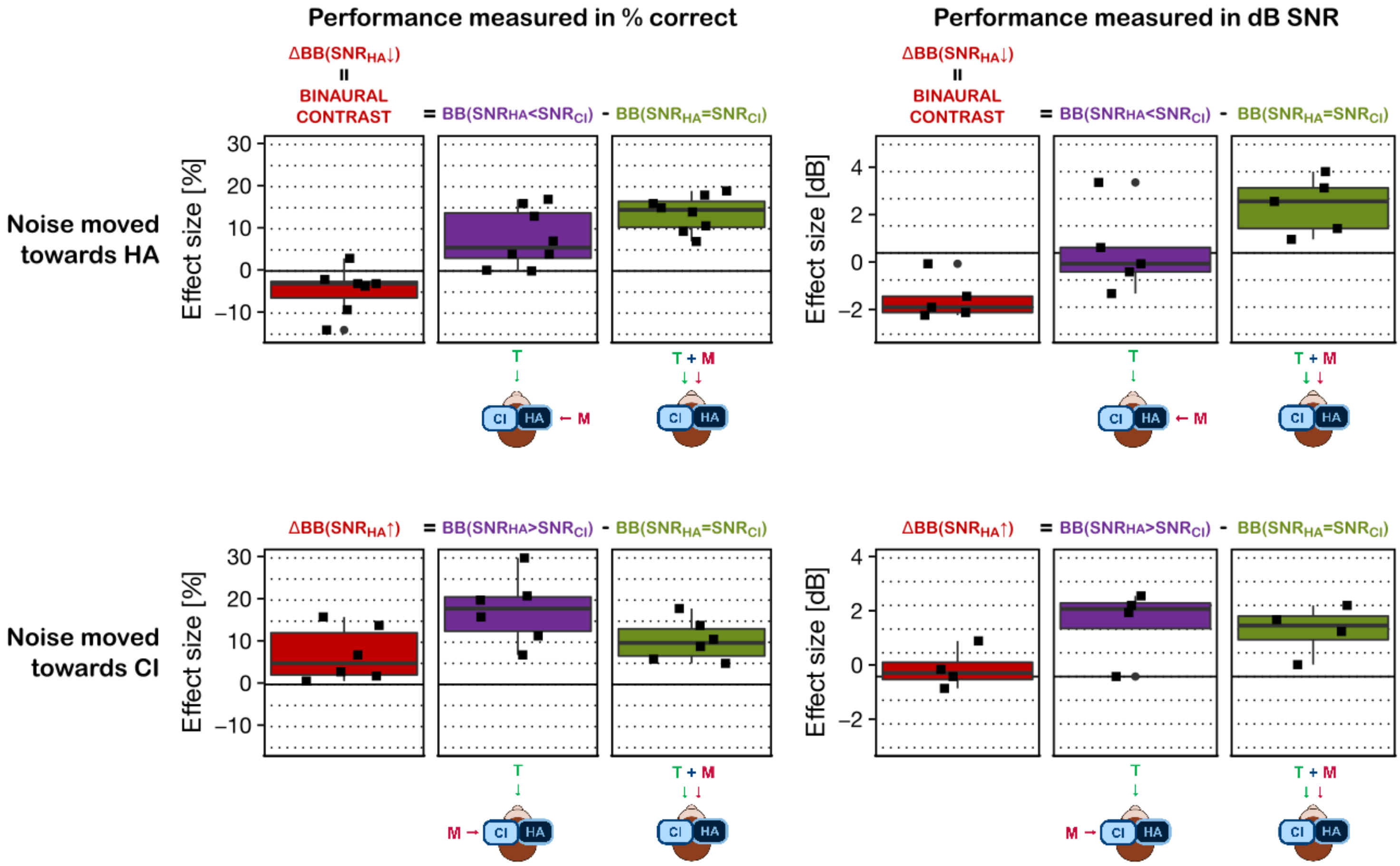

Figure 3: Bimodal benefits for different noise locations, and within-study differences in bimodal benefit. Bimodal benefit appears to be largest when adding an ear with better SNR ($BB(SNR_{HA} > SNR_{CI})$), smallest when adding an ear with lower SNR ($BB(SNR_{HA} < SNR_{CI})$, often reported as "squelch"), and somewhere in between when adding an ear with equal SNR ($BB(SNR_{HA} = SNR_{CI})$, often reported as "redundancy" or "summation"). This suggests that the bimodal benefit might be a simple function of the signal-to-noise ratio at the hearing aid side, and there is no binaural cue processing involved, i.e., no binaural unmasking in bimodal listeners. Data are from Tyler et al. (2002), Morera et al. (2005), Dunn et al. (2005), Litovsky et al. (2006), Mok et al. (2006), Yuen et al. (2009), Mok et al. (2010), Morera et al. (2012), Gifford et al. (2014), Kokkinakis et al. (2014), Pyschny et al. (2014).

Therefore, we hypothesize that no significant processing of interaural differences (i.e., no binaural unmasking) is involved in any bimodal benefit. This hypothesis is further supported by the fact that bimodal listeners are poor performers in localization and binaural cue perception (Francart et al., 2008, 2009). Instead, we hypothesize that bimodal benefits are (almost) completely mediated by the provision of complementary cues, and the magnitude of the benefit is a simple function of the quality of these complementary cues, in particular, the SNR at the hearing aid side.

In this work, we performed two experiments with acoustic simulations of bimodal listening to further test our hypotheses. In the first experiment, we measured all above-defined measures in different masker types to demonstrate how our framework allows to disentangle the different effects involved in spatial release from masking and to measure binaural contrast explicitly within subjects. In the second experiment, we measured again the bimodal benefit in different masker types, for different realistic (but broadband) SNR offsets at the hearing aid side with respect to the CI side.

II. General Methods

A. Participants

All participants were normal-hearing listeners, having pure-tone hearing thresholds better than 20 dBHL at all octave audiometric frequencies from 250 to 8000 Hz. They were aged between 18 and 25 years old. Both experiments had a different set of participants. The study has been approved by the Ethics Committee Research UZ/KU Leuven (project number S58970).

B. Apparatus

All experiments took place in a double-walled soundproof booth. Stimuli were presented through Sennheiser HDA200 over-the-ear headphones via an RME Hammerfall DSP Multiface soundcard, using the software platform APEX 3 (Francart et al., 2008).

C. Simulation of bimodal hearing

We simulated bimodal hearing with a noise band vocoder in one ear (CI) and a low-pass filter in the other ear (hearing aid).

CI listening was simulated in the left ear with a N-channel noise band vocoder (the number of channels differed across experiments, as explained in the respective method sections): the input signal was sent through a filter bank (constructed with 4^{th}-order Butterworth filters), logarithmically spaced between 125 Hz and 8000 Hz; within each channel, the envelope was detected with half-wave rectification followed by a 50 Hz low-pass filter (4^{th}-order Butterworth filter); this envelope was used to modulate a noise band of which the spectrum corresponded to the respective channel; the outputs of all channels were summed to obtain a single acoustic signal.

Severe hearing loss was simulated in the right ear with a low-pass filter with a cutoff frequency of 500 Hz. We designed the filter with a steep cutoff, such that the attenuation was 50 dB or more starting from around 650 Hz.

The simulation characteristics were chosen such that the CI side contributed the most to speech understanding, and speech understanding in quiet with hearing aid-only was below 50%. This was verified in a pilot test with a Dutch monosyllabic word test (NVA words, see Wouters et al., 1994), and with a Matrix sentence test (Luts et al., 2015).

D. Stimuli

We used exactly the same stimuli as we did for normal-hearing listeners in a previous experiment (Dieudonné & Francart, 2018b). For target speech, we used the Flemish (Dutch) Matrix sentence test (Luts et al., 2015). It consists of 13 lists of 20 sentences uttered by a female speaker. Each sentence has the same grammatical structure (name, verb, numeral, adjective, object). As the semantic content makes little sense and is very similar across the 260 different sentences (e.g., “David has eight yellow boats”), participants do not learn the content. Moreover, the order of the

20 sentences within a list is randomized for every condition, such that this cannot be learned either. Altogether, this means that lists can be reused between conditions. For the masker, we compared three different masker types: stationary speech-weighted noise (SWN), a competing talker and modulated SWN.

The SWN was a stationary noise and had the same long-term average speech spectrum as the Matrix sentences (Luts et al., 2015). As such, we could measure the mere effect of energetic masking.

The competing talker was a Swedish story uttered by a female speaker. We chose Swedish because it is also a Germanic language like Dutch, but our participants likely could not understand it. In this way, we could investigate the effect of temporal fine structure of speech, while not having informational masking due to failure of object selection (Francart et al., 2011). The masker was chosen such that the fundamental frequency was comparable to that of target speech: around 200 Hz (calculated using Praat (Boersma et al., 2002)). We reduced silent gaps longer than 100 ms to 100 ms[‡‡], flattened the time-dependent root-mean-square level[§§], and filtered the signal to obtain the same average spectrum as the SWN. The story still sounded like natural speech after these operations.

The modulated SWN was constructed by modulating the stationary SWN with the broadband temporal envelope of the competing talker. We determined this envelope by full-wave rectification and low-pass filtering (cutoff 50 Hz) of the competing talker signal. We chose this masker to investigate the effect of temporal gaps separately, without having the effect of informational masking or temporal fine structure in the masker. In the end, all maskers had the same long-term average spectrum and the same root-mean-square level.

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‡‡ A silent gap was defined as a part of the signal where the absolute value of the signal was below a certain threshold – around 20 dB below the root-mean-square level of the total signal – for 100 ms or longer. The threshold was set such that these gaps were indeed gaps between words, as verified by visual inspection.

§§ Root-mean-square level was calculated in blocks of 500 ms, then smoothed with a moving average filter with a length of 2 s. The inverse of these levels was applied as a gain on the signal, to obtain a flattened sound level over the course of the story.

E. Procedure

Before the actual measurements, listeners got used to the simulation of bimodal hearing by listening to a story of around 5 minutes. The first minute of the story, they were allowed to read the story simultaneously while listening to it. After the story, some short questions were asked to make sure that the listener was able to understand speech with the simulation.

Then, we measured the speech reception threshold (SRT) – i.e., the SNR at which 50% of speech could be understood – for each condition with an adaptive procedure (Brand & Kollmeier, 2002). Each measurement consisted of 20 trial sentences. The first trial sentence was repeated until the word score was above the target word score (i.e., 50%). For each trial, the magnitude of the SNR-adaptation Δ_{SNR} was set according to the following equation (Brand & Kollmeier, 2002):

$$\Delta_{SNR} = -10 * 1.41^{-i} * (prev - tar)$$

with i the number of reversals at the current trial, $prev$ the participant's word score of the previous trial (between 0/5 and 5/5), and tar the target word score (i.e., 50%). This means that the SNR-adaptation was smaller for scores closer to 50%, and got smaller towards the end of the procedure. The numerical values are set to obtain optimal convergence of the procedure, assuming an underlying psychometric curve with a slope of 15%/dB. The target speech was presented continuously at a level of 60 dB(A) during each run, while the masker level was set according to the presented SNR. For each measurement, we estimated the SRT as the SNR after the last trial.

III. Experiment 1: Spatial cues

In our first experiment, we measured all spatial effects as defined in **Figure 2** in different masker types to demonstrate how our framework is able to disentangle the different effects involved in spatial release from masking for bimodal listeners, and to measure binaural contrast explicitly.

A. Methods

A. 1. Participants

Ten normal-hearing listeners participated in this experiment, aged between 18 and 25 years old.

A. 2. Simulation of bimodal hearing

The acoustic simulation of bimodal hearing is described in **section II.C**. In this experiment, we used a 6-channel noise vocoder for the simulation of CI listening.

A. 3. Simulation of spatial hearing

We simulated spatial hearing with head-related transfer functions (HRTFs) that were constructed in previous work with normal-hearing listeners (Dieudonné & Francart, 2018b). With HRTFs, the SNR (which is varied in the adaptive procedure) is the SNR before HRTF processing, which corresponds with the SNR at the center of the listener's head if the test were conducted in free-field.

We measured the HRTFs of a human-like acoustical manikin (head and torso) in a localization arc, for sounds coming from 0° and 90° in the azimuthal plane, corresponding to sounds coming from the front and from the hearing aid side respectively. Loudspeakers were placed at a distance of 1 m from the center of the manikin's head while at the same height as its ears. To ensure exact symmetry, the HRTF for sounds coming from the CI side was constructed by swapping the left and right ear channels of the HRTF for sounds coming from the hearing aid side.

A. 4. Conditions

A condition was defined by three factors: masker type (SWN, modulated SWN, or Swedish competing talker), ears (CI-only or bimodal) and direction of arrival of the masker (front, hearing aid-side or CI-side). Target speech was always presented from the front. For each noise type, we coded the results as SRT(ears,direction of arrival). An overview of all conditions is given in **Table 1**.

Table 1: An overview of the different conditions that were tested for each noise type in Experiment 1.

	CI-only	bimodal
noise from front	SRT(CI-only,front)	SRT(bimodal,front)
noise from hearing aid-side	SRT(CI-only,hearing aid-side)	SRT(bimodal,hearing aid-side)
noise from CI-side	SRT(CI-only,CI-side)	SRT(bimodal,CI-side)

For each participant, we performed each measurement twice to test for learning effects and to reduce random variability in the results. We ended up with a total of 3 (noise types) × 6 (SRTs(ears,direction of arrival)) × 2 (repetitions) = 36 measurements for each subject. We performed the tests in blocks per noise type, while randomizing the order of these blocks and randomizing the order of conditions within each block. Before each block, the participants did 2 training measurements (of the condition SRT(bimodal,front)) to get used to the respective noise type.

A. 5. Calculation of spatial effects

We calculated the magnitude of each spatial effect according to our theoretical framework of SRM in asymmetric hearing (**Figure 2**). An overview of all definitions is given in **Table 2**. We quantify each effect as the difference between two SRTs (or between two effects, for binaural contrast and the difference in bimodal benefits), such that a positive value corresponds to an improvement in speech intelligibility due to the respective spatial effect.

Table 2: An overview of all spatial effects, according to the theoretical framework of Figure 2. A positive value corresponds to an improvement in speech intelligibility due to the respective spatial effect.

Effect size [dB SNR]	
SRM_{HA}	= -[SRT(bimodal,hearing aid-side) - SRT(bimodal,front)]
SRM_{CI}	= -[SRT(bimodal,CI-side) - SRT(bimodal,front)]
$HS(SNR_{CI}\uparrow)$	= -[SRT(CI-only,hearing aid-side) - SRT(CI-only,front)]
$HS(SNR_{CI}\downarrow)$	= -[SRT(CI-only,front) - SRT(CI-only,CI-side)]
$BB(SNR_{HA} = SNR_{CI})$ (redundancy)	= -[SRT(bimodal,front) - SRT(CI-only,front)]
$BB(SNR_{HA} < SNR_{CI})$ (squelch)	= -[SRT(bimodal,hearing aid-side) - SRT(CI-only,hearing aid-side)]
$BB(SNR_{HA} > SNR_{CI})$	= -[SRT(bimodal,CI-side) - SRT(CI-only,CI-side)]
binaural contrast = $\Delta BB(SNR_{HA}\downarrow)$	= $BB(SNR_{HA} < SNR_{CI}) - BB(SNR_{HA} = SNR_{CI})$
$\Delta BB(SNR_{HA}\uparrow)$	= $BB(SNR_{HA} > SNR_{CI}) - BB(SNR_{HA} = SNR_{CI})$

B. Results

Our most important finding was that SRM could be characterized as a trade-off between a change in SNR at the CI side (represented by the *head shadow*) and an opposite change in SNR at the HA side (represented by the *change in bimodal benefit*), such that SRM was always rather small. Moreover, we measured binaural contrast explicitly, and it was negative for all masker types. Our analyses are explained in detail below.

We did all analyses by means of linear mixed models with subject as random effect to account for within-subject correlation. When investigating the effect of noise type, we took *modulated SWN* as baseline condition, such that we could investigate the effect of temporal silent gaps on the one hand (by comparing with *SWN*), and temporal fine structure of speech (and informational masking) on the other hand (by comparing with *competing talker*). We report our data as mean values ± 1 standard deviation. A difference is considered significant if $p < 0.05$.

B. 1. Learning effect

We investigated the learning effect in our experiment, by calculating the difference between repetitions (test and retest) within the same condition. We fitted a linear mixed model with variable SRT as a function of the factor repetition (2 levels). We found a significant learning effect of 2.36 ± 2.67 dB SNR [$t(349)=4.71$, $p<0.001$]. We continued the analysis by verifying a possible interaction of the factor repetition with noise type (3 levels) and/or condition (6 levels), by fitting a linear mixed model with variable SRT as a function of repetition, noise type, condition, and the two interactions. Here, we found that neither of the interactions were significant predictors of the SRT [$F(2,335)=2.56$, $p=0.07$ and $F(5,335)=0.78$, $p=0.57$]. This could be expected, as we randomized the order of conditions for each subject and for each repetition within each subject. Therefore, we concluded that we could average test and retest for all other analyses, without introducing any relevant bias due to learning. By averaging the results of two repetitions, random variability in the results should be reduced, increasing the statistical power of further analyses. The resulting SRTs are reported in **Table 3**.

Table 3: Mean and standard deviation (s.d.) [dB SNR] of speech reception thresholds for the different spatial conditions.

	SWN				Modulated SWN				Competing talker			
	CI-only		bimodal		CI-only		bimodal		CI-only		bimodal	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Noise from front	0.3	1.6	-3.7	1.4	1.9	2.6	-4.2	2.4	7.4	1.9	2.1	1.6
Noise from CI-side	5.1	2.4	-0.4	1.2	6.3	3.8	-1.3	2.4	10.4	2.6	3.1	1.8
Noise from hearing aid-side	-2.4	2	-4.4	1.2	-1.2	3.3	-4.6	2.1	4	1.8	0.4	1.8

B. 2. Speech reception thresholds

To compare our vocoder simulation with real CI listeners, we investigated the effect of masker type on the SRTs in the CI-only condition with both speech and noise coming from the frontal direction (**Figure 4**). We fitted a linear mixed model with variable SRT (only for the CI-only condition with noise from front) and factor noise type. Noise type was a significant predictor of the SRT in our model [$F(2,18)=53.07$, $p<0.001$]. The SRT was significantly smaller (better) for SWN as compared to modulated SWN [$t(18)=-2.19$, $p=0.04$], while it was significantly larger (worse) for the competing talker as compared to modulated SWN [$t(18)=7.62$, $p<0.001$].

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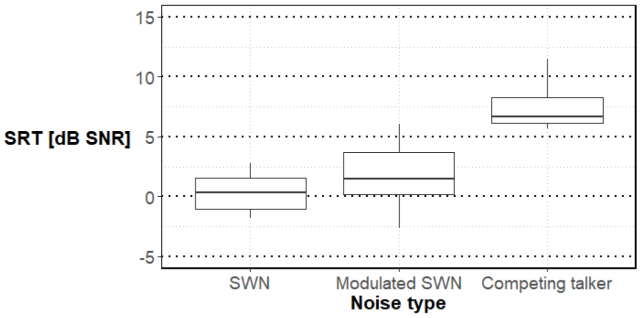

Figure 4: Speech reception thresholds (SRTs) with the CI only for collocated target and masker, in different noise types. Higher SRTs correspond to worse intelligibility. It can be seen that speech understanding is worse in modulated noise than in stationary noise, and the worst with a competing talker. This is the opposite of what is observed for normal-hearing listeners.

B. 3. Spatial effects

For the following analyses, we transformed our SRTs to the different spatial effects according to our semantic framework of **Figure 2** with the formulae of **Table 2**. The results are shown in **Table 4** and **Figure 5**.

Table 4: Different spatial effects [dB SNR] according to our framework for bimodal listeners (**Figure 2**), obtained with the equations of **Table 2**.

	SWN		**Modulated SWN**		**Competing talker**	
	mean	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**
HS(SNR_{CI}↑)	2.7	1.4	3.1	3	3.4	1.5
HS(SNR_{CI}↓)	-4.9	1.7	-4.4	3.6	-3	1.9
BB($SNR_{HA} = SNR_{CI}$) (redundancy)	4	1.3	6.1	2.1	5.3	2.2
BB($SNR_{HA} < SNR_{CI}$) (squelch)	2.1	1.1	3.3	2.5	3.6	2.3
BB($SNR_{HA} > SNR_{CI}$)	5.6	1.7	7.6	3.3	7.3	2.3
ΔBB(SNR_{HA}↓) (binaural contrast)	-2	1.8	-2.8	3.1	-1.8	2.3
ΔBB(SNR_{HA}↑)	1.6	1.8	1.4	4.5	1.9	1.9
SRM_{HA}	0.7	0.9	0.4	2	1.7	1.5
SRM_{CI}	-3.3	0.8	-3	2.3	-1.1	1.1

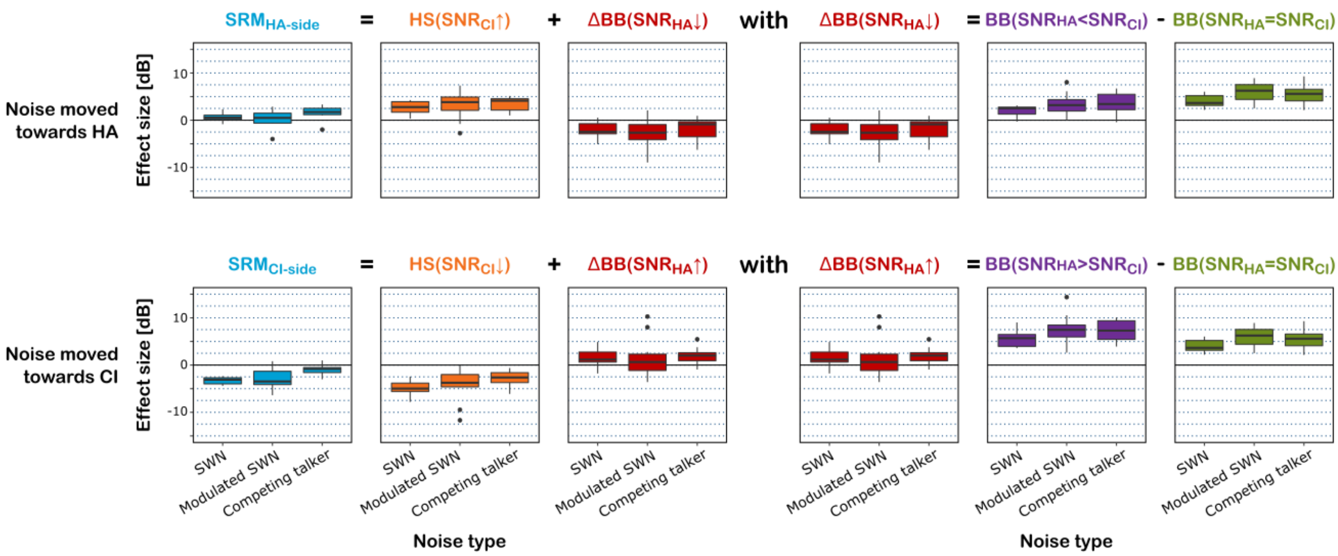

Figure 5: Different spatial effects according to our framework for bimodal listeners (**Figure 2**), obtained with the equations of **Table 2**. The top row are the results for noise moved towards the hearing aid side (**Figure 2(a)**), while the bottom row are the results for noise moved towards the CI side (**Figure 2(b)**). For both cases, spatial release from masking (SRM) can be explained as a trade-off between (1) a monaural change in SNR at the CI side (resulting in the head shadow benefit or disadvantage) and (2) an opposite change in SNR at the hearing aid side (resulting in a change in bimodal benefit as compared to listening with spatially collocated target and masker).

B.3.1 *Noise at the hearing aid side*

The case of noise moved towards the hearing aid side is analyzed according to the framework of **Figure 2(a)**.

We found that SRM_{HA} (for the baseline condition of modulated SWN) was not significantly different from 0 [$t(18)=0.719$, $p=0.48$], and there was no significant effect of noise type [$F(2,18)=1.86$, $p=0.18$]. There was a significantly positive $HS(SNR_{CI}\uparrow)$ [$t(18)=4.72$; $p<0.001$], and a significantly negative $\Delta BB(SNR_{HA}\downarrow)$ [$t(18)=-3.53$; $p=0.002$]. Noise type had no significant effect on either of these two [$F(2,18)=0.32$, $p=0.73$ and $F(2,18)=0.46$, $p=0.64$, respectively].

We found that both bimodal benefits BB(SNR_{HA} < SNR_{CI}) and BB(SNR_{HA} = SNR_{CI}) were significantly larger than 0 [$t(18)=5.13$, $p<0.001$ and $t(18)=9.96$; $p<0.001$ respectively]. For both bimodal benefits, noise type was not a significant predictor [$F(2,18)=2.22$, $p=0.14$ and $F(2,18)=2.97$, $p=0.08$ respectively].

B.3.2 *Noise at the CI side*

The case of noise moved towards the CI side is analyzed according to the framework of **Figure 2(b)**.

We found that SRM_{CI} (for the baseline condition of modulated SWN) was significantly smaller than 0 [$t(18)=-6.13$; $p<0.001$]. Noise type was a significant predictor of SRM_{CI} [$F(2,18)=6.71$, $p=0.007$], with SRM_{CI} significantly larger (here: closer to zero) for a competing talker [$t(18)=2.88$, $p=0.01$], and not significantly different for SWN [$t(18)=-0.53$; $p = 0.6$], both as compared to modulated SWN.

There was a significantly negative HS(SNR_{CI}↓) [$t(18) = -5.474$; $p<0.001$], but no significant ΔBB(SNR_{HA}↑) [$t(18) = 1.52$; $p = 0.146$]. Noise type had no significant effect on either of these two [$F(2,18)=1.5$, $p=0.25$ and $F(2,18)=0.07$, $p=0.94$, respectively].

We found that bimodal benefit BB(SNR_{HA} > SNR_{CI}) was also significantly larger than 0 [$t(18)=9.38$; $p<0.001$], with a significant effect of noise type [$F(2,18)=3.62$, $p=0.048$]. BB(SNR_{HA} > SNR_{CI}) was significantly smaller for SWN [$t(18)=-2.5$; $p = 0.02$], but not significantly different for a competing talker [$t(18)=-0.37$, $p=0.71$], both as compared to modulated SWN. BB(SNR_{HA} = SNR_{CI}) was significantly larger than 0, with no effect of noise type, as discussed in **B.2.1**.

C. Discussion

C. 1. Speech reception thresholds

For normal-hearing listeners, monaural speech perception improves with modulated noise as compared to stationary noise, and improves even more for a competing talker as compared to the other two maskers, a phenomenon that is known as masking release (Festen & Plomp, 1990). Hearing-impaired listeners have little-to-no benefit of masking release, and CI users experience the exact opposite phenomenon: for them, speech maskers are the most effective in masking other speech, and modulated interferers are more effective maskers than stationary noise (Qin & Oxenham, 2003; Stickney et al., 2004). This is in agreement with our vocoder simulation of CI-only listening, as can be seen in **Figure 4**.

C. 2. Spatial effects

Considering the *head shadow* effect, it is clear that moving the masker towards the hearing aid side increases the SNR at the CI side, resulting in a positive head shadow benefit; moving the masker towards the CI side decreases the SNR at the CI side, resulting in a negative head shadow effect. While the change in SNR is frequency-dependent due to head diffraction, and the importance of different frequency bands to understand speech depends on the masker type (ANSI, 1997; Dieudonné & Francart, 2018b), we found no effect of masker type on the head shadow effect here. For the *bimodal benefit*, we observe a similar SNR dependency: the benefit of adding the hearing aid is the largest when the masker is located at the CI side, smallest when the masker is located at the hearing aid side, and somewhere in between when the masker is in front of the listener. This is in agreement with the literature on real bimodal listeners (see **Figure 3**). Although only statistically significant when the masker is at the CI side, the bimodal benefit is larger for modulated maskers than for stationary maskers, whether or not the modulated masker is speech. This supports the hypothesis that the supply of low frequency temporal fine structure improves the ability to glimpse the target in a modulated masker (Kong & Carlyon, 2007; Li & Loizou, 2008; Sheffield & Gifford, 2014). Our data does not suggest any form of binaural cue processing, as *binaural contrast* (=ΔBB(SNR_{HA}↓)) is always negative. Although binaural contrast has never been measured explicitly in bimodal listeners to our knowledge, this result seems to be in agreement with data from the literature (see **section I.C**).

Altogether, our framework is able to show that there is probably no binaural unmasking involved in SRM for bimodal listeners. Instead, SRM is a trade-off between a change in SNR at the CI side due to the head shadow, and a difference in bimodal benefit, supposedly also mediated by a change in SNR offset at the hearing aid side. In other words, the change in SNR at the CI side is partly compensated by the opposite change in SNR at the hearing aid side, resulting in small (to non-significant) SRM. This can be seen in simulated bimodal listeners (as discussed here) as well as real bimodal listeners (as discussed in **section I.C**).

In Experiment 2, we investigate more systematically how the bimodal benefit is influenced by the SNR offset at the hearing aid side.

IV. Experiment 2: SNR adaptation

In our second experiment, we measured again the bimodal benefit in different masker types, for different realistic (but broadband) SNR offsets at the hearing aid side with respect to the CI side. Here, we only considered two noise types: SWN and a (Swedish) competing talker.

A. Methods

A. 1. Participants

Twelve normal-hearing listeners participated in this experiment, aged between 18 and 25 years old. None of these participants took part in Experiment I.

A. 2. Simulation of bimodal hearing

The acoustic simulation of bimodal hearing is described in **section II.C**. In this experiment, we used a 5-channel noise vocoder for the simulation of CI listening.[***]

A. 3. Conditions

A condition was again defined by three factors: masker type (SWN or Swedish competing talker), ears (CI-only or bimodal) and broadband SNR offset at the hearing aid side (+2, 0, -3, -5 and -10 dB SNR). We varied the SNR offset by adapting the level of the masker at the hearing aid side separately; as such, the SNR can also be considered as an interaural level difference of the masker. The SNR to calculate the SRT is now the SNR at the CI side. Therefore, only one CI-only condition needs to be measured (per noise type); the bimodal benefit can be calculated for all SNR offsets at the hearing aid side w.r.t. this one CI-only condition.

The broadband SNR offsets at the hearing aid side were chosen to correspond to realistic listening conditions: target and masker in front of a listener corresponds to an offset of 0 dB SNR; target in front and masker at the hearing aid side corresponds to an offset of -5 dB SNR; target in front and masker at the CI side corresponds to an offset of +2 dB SNR. Note that the SNR improvement at the hearing aid side due to the head shadow effect is smaller, because the head shadow is not as effective in the low frequencies that correspond to the residual hearing of the typical bimodal listener that we consider here. Then, we considered for each condition an extra SNR deterioration at the hearing aid side of 5 dB (which might for example be the result of different microphone directionality settings at the hearing aid side as compared to the CI side), corresponding to offsets of respectively -5 dB (which is already considered), -10 dB and -3 dB SNR.

[***] In a pilot experiment with 4 listeners, we wanted to verify whether the effect of the SNR offset at the hearing aid side was dependent on the speech perception with the CI only. Therefore, we varied the number of channels between 5 and 8. While speech perception with the CI-only was clearly better with more channels (a difference of around 4 dB SNR), the effect of the SNR offset at the hearing aid side did not appear to depend on the number of channels. Therefore, we decided to perform the rest of the experiments only for the case of 5 channels.

For each participant, we performed each measurement twice to test for learning effects and to reduce random variability in the results. We ended up with a total of 2 (noise types) × [5 (SNR offsets) + 1 (CI-only)] × 2 (repetitions) = 24 measurements for each subject. We performed the tests in blocks per noise type, while randomizing the order of these blocks and randomizing the order of conditions within each block. Before each block, the participants did 2 training measurements (a bimodal condition with no SNR offset at the hearing aid side) to get used to the respective noise type.

B. Results

Our most important finding of Experiment 2 was that the bimodal benefit was linearly dependent on the SNR offset at the hearing aid side (with respect to the CI side), i.e., a simple function of SNR. While the bimodal benefit was dependent on masker type, the linear dependence (the slope of the curve) was independent of masker type. Our analyses are explained in detail below.

Similar to Experiment 1, we conducted all analyses again by means of linear mixed models with subject as random effect to account for within-subject correlation. We report our data as mean values ± 1 standard deviation. A difference is considered significant if $p < 0.05$.

B. 1. Learning effect

We investigated again the learning effect in our experiment, by calculating the difference between repetitions (test and retest) within the same condition. We fitted a linear mixed model with variable SRT as a function of the factor repetition (2 levels). Here, we found no significant learning effect [$t(275)=0.54$, $p=0.59$], such that we concluded that we could average test and retest for all other analyses. The resulting SRTs are reported in **Table 5**.

B. 2. Speech reception thresholds

We investigated the effect of masker type on the SRTs in the CI-only condition (**Figure 6**). We fitted a linear mixed model with variable SRT and factor noise type. Noise type was a significant predictor of the SRT in our model [t(11)=10.26, p<0.001].

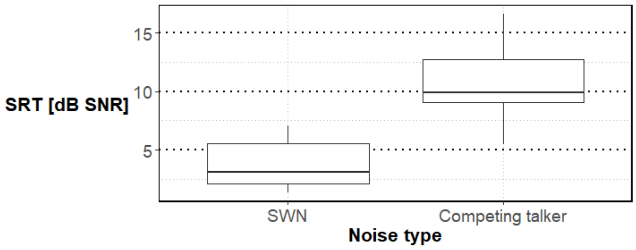

Figure 6: Speech reception thresholds (SRTs) with the CI only in different noise types. As higher SRTs correspond to worse intelligibility, it can again be seen that a competing talker is the most effective masker. SRTs are slightly worse in Experiment 2 as compared to Experiment 1 because the vocoder contained less channels in Experiment 2.

B. 3. Bimodal benefits

For the following analyses, we calculated the bimodal benefit (difference in SRT between bimodal listening and CI-only listening) for each SNR offset at the hearing aid side. The results are shown in **Table 5** and **Figure 7**.

Table 5: Mean and standard deviation (s.d.) [dB SNR] of speech reception thresholds and bimodal benefits for the different SNR offsets at the hearing aid side.

		SWN				Competing talker			
	SNR offset at hearing	**SRT**		**Bimodal benefit**		**SRT**		**Bimodal benefit**	
Devices	**aid side**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**	**mean**	**s.d.**
CI-only	/	3.6	2.0	/	/	10.7	3.2	/	/
Bimodal	**-10**	1.6	1.8	2.1	0.8	5.4	2.2	5.4	3.3
	-5	-0.1	1.3	3.8	1.2	4.5	2.5	6.2	3.2
	-3	-1.1	1.1	4.7	1.5	3.4	3.7	7.3	3.3
	0	-2.6	1.4	6.3	1.3	2.2	2.9	8.5	3.9
	2	-2.6	2.2	6.2	1.7	1.5	2.7	9.2	3.8

We fitted a linear mixed model to assess the effect of SNR offset at the hearing aid side (which we treated as a continuous variable), the type of noise and the interaction between these two factors. We found that the bimodal benefit for the baseline condition (speech understanding in SWN with an SNR offset of 0 dB at the hearing aid side) was 5.8 dB SNR, significantly larger than 0 [t(105)=9.6, p<0.001]. We also found that the SNR offset at the hearing aid side was a significant predictor of the bimodal benefit [t(105)=6.65, p<0.001], with a regression slope of 0.38 dB/dB. This means that every decibel increase in SNR at the hearing aid side results in approximately 0.38 dB increase in bimodal benefit (and thus increase in SRT). Noise type was also a significant predictor of the bimodal benefit, with a bimodal benefit that was on average 2.6 dB larger for a competing talker than for SWN [t(105)=6.61, p<0.001]. There was no significant interaction between the noise type and the SNR offset at the hearing aid side [t(105)=-0.52, p=0.60].

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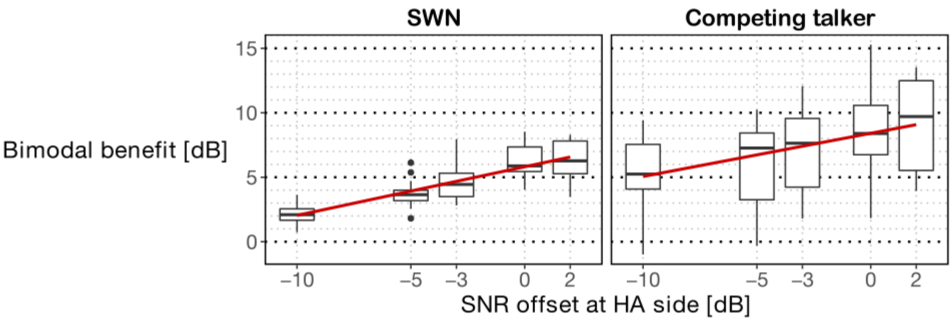

Figure 7: Bimodal benefits for different SNR offsets at the hearing aid side and for different masker types. Bimodal benefit is higher for the more distractive masker, i.e., the benefit of the hearing aid is greater for a competing talker than for SWN. Moreover, the bimodal benefit appears to be dependent on the SNR offset at the hearing aid side in a linear way: the higher the SNR at the hearing aid side, the higher the bimodal benefit.

C. Discussion

We observe again that the bimodal benefit is larger for a competing talker than for stationary SWN, as in Experiment 1. If we compare the results of Experiment 1 and 2 quantitatively, we observe that we obtain higher (worse) SRTs in the CI only condition in Experiment 2, and larger (better) bimodal benefit in Experiment 2. Both can be explained by the lower number of vocoder channels (5 instead of 6) in Experiment 2 (Yoon et al., 2015).

Most interestingly, we observe a clear dependence of the bimodal benefit on the SNR offset at the hearing aid side. This dependence appears to be linear, and we found a regression slope of around 0.4 dB/dB: every 1 dB increase in SNR offset at the hearing aid side results in approximately 0.4 dB increase in SRT. Moreover, this linear dependence appears to be independent of the masker type, i.e., the slope of the trend line (**Figure 7**) is independent on the baseline performance with the CI only. In a pilot experiment, we extended the CI only baseline performance to a larger range by varying the amount of vocoder channels; here, we did not find an effect on the slope either.

On the other hand, if we would vary the contribution of the hearing aid (by varying the cut-off frequency of the low pass filter), one could imagine that the slope would vary over a continuum between 0 (if the hearing aid has no contribution) and close to 1 (if speech intelligibility is completely determined by the hearing aid, e.g., with a higher low pass cut-off). In fact, considering the two rightmost boxplots of **Figure 7** (competing talker with SNR offset of 0 dB and 2 dB), i.e., the conditions where one would expect the largest contribution of the hearing aid, it looks like the slope might be increasing: the rightmost boxplot is slightly above the red line.

V. General Discussion

An increasing number of CI users wear a hearing aid in the non-implanted ear, resulting in the so-called bimodal benefit: improved localization ability (or spatial awareness) and improved speech intelligibility (Ching et al., 2004, 2007). This is because the two devices deliver complementary information as well as binaural information (Francart & McDermott, 2013; Van Hoesel, 2012). Considering the bimodal benefit in speech intelligibility (benefit of listening with two ears instead of only the CI), it is not yet known what information is used exactly, and in which manner. Although performance is often explained in terms of spatial attention, binaural processing, etc. – as a direct translation from normal-hearing listeners' mechanisms –, we assert that no complex binaural or spatial processing is involved in any bimodal benefit. Instead, speech intelligibility is mediated by monaural signal-to-noise ratios, simple as that.

To support our hypotheses, we reviewed an extensive selection of the literature with a recently developed theoretical framework (Dieudonné & Francart, 2018b), followed by two experiments with simulated bimodal listeners (with poor residual hearing in the non-implanted ear). We first discuss the results of our experiments, so that we can conclude with the translation towards real bimodal listeners based on the relevant literature, and finally the clinical relevance of our results.

A. Effect of monaural signal-to-noise ratios for simulated bimodal listeners

In the first experiment, we analyzed speech intelligibility in noise in different realistic spatial set-ups (with HRTFs), according to the semantic framework that we proposed in earlier work (Dieudonné & Francart, 2018b; **Figure 1**). Within this framework, we emphasize that *binaural squelch* (in its often-used definition, see **section I.A**) is not necessarily the result of binaural cue processing. Instead, we defined *binaural contrast* as a measure to quantify the benefit of binaural cue processing: the difference between spatial release from masking and head shadow, or equivalently, the difference between squelch and redundancy (the exact definitions are given in **Table 2**). Although we could indeed measure squelch (here referred to as a bimodal benefit with lower SNR at the hearing aid: $BB(SNR_{HA} < SNR_{CI})$), we found no binaural contrast in our simulated bimodal listeners, irrespective of the masker type. Moreover, we observed that the bimodal benefit was largest when the masker was at the CI side, smallest when the masker was at the hearing aid side, and somewhere in between when the masker was in front of the listener. This supports our hypothesis that bimodal benefit is mediated by the signal-to-noise ratio at the hearing aid side, rather than that it is the result of binaural cue processing.

In the second experiment, we explicitly investigated the relationship between the SNR at the hearing aid side and the bimodal benefit. We measured the bimodal benefit for different SNR offsets at the hearing aid side with respect to the CI side (in other words, different interaural level differences of the masker). Here, we varied the SNR offsets in a broadband manner (i.e., independent of frequency), in contrast to the more realistic listening conditions of the first experiment. We found a clear and linear dependence of the bimodal benefit on the SNR offset at the hearing aid side, such that every dB increase in SNR offset at the hearing aid side resulted in approximately 0.4 dB increase in SRT. Moreover, this dependency was independent of the masker type. This agrees with the observation in Experiment 1 that the change in bimodal benefit due to a change in SNR at the hearing aid (ΔBB, which is the equivalent of the regression slope in Experiment 2) was independent of the masker type.

When comparing both experiments, we have to take into account two main differences between free-field (or HRTF) listening and varying the broadband SNRs.

First, free-field (or HRTF) listening with spatially separated target and masker results in frequency-dependent SNR offsets due to head diffraction (i.e., the SNR offset is smaller for low frequencies). To be able to predict the bimodal benefit in realistic free-field conditions, one would need a frequency-dependent weighting for the SNR at the hearing aid side (similar to the weights in the speech intelligibility index, ANSI (1997)). Future speech intelligibility models for bimodal listeners could include such a frequency-dependent weighting for the SNR at the hearing aid side. Modeling speech intelligibility in bimodal listeners as the sum of an SNR-dependent monaural (CI only) intelligibility and an SNR-dependent bimodal benefit might simplify existing models, as they currently also take into account a binaural equalization-cancellation stage (Williges et al., 2015; Zedan et al., 2018).

Second, free-field (or HRTF) listening also provides interaural time differences. However, in our simulation of bimodal hearing little to no ITDs could be perceived: (1) the vocoder removed all temporal fine structure, removing low frequency ITDs, and (2) the low pass filter removed high frequencies, such that high frequency envelope cues were also rendered imperceptible. Moreover, in a pilot experiment with 4 listeners, we found that removing ITD cues from the HRTFs (using the same methods as Dieudonné & Francart, 2018b) did not affect the performance. This is in agreement with real bimodal listeners that have little to no ITD sensitivity with current clinical devices in realistic listening conditions (Francart et al., 2009; Van Hoesel, 2012).

Similarly to normal-hearing listeners (Dieudonné & Francart, 2018b), if ITDs are not presented or cannot be perceived, there appears to be no binaural cue processing in speech understanding, as represented by the absence of binaural contrast. Interaural level differences have little to no binaural contribution to speech understanding.

B. Translation towards real bimodal listeners

One should always be cautious with the interpretation of vocoder simulations, in particular when considering binaural hearing. Moreover, our experiment differs from others in terms of speech and noise material, psychoacoustic procedure (constant or adaptive), simulation parameters, processing of the devices (e.g., directionality of microphones and gain compression), room characteristics (e.g., reverberation time), degree of residual hearing, and so on. Therefore, an extensive *quantitative* comparison with other studies would be almost meaningless (there is always a way to explain things given this number of degrees of freedom) and would not provide us with more insights on how our study compares with the literature. However, *qualitatively*, the results of our first experiment correspond well with what has been observed for real bimodal listeners (for an overview of the relevant literature, see **section I.C**)**:** bimodal benefit is largest when the masker is at the CI side, smallest when the masker is at the hearing aid side, and somewhere in between when the masker is in front of the listener. Although these three cases are often discussed separately – and with separate names: head shadow, squelch and redundancy respectively – this observation already suggests that they can be interpreted as three times the same mechanism: a bimodal benefit resulting from (monaural) complementary information that is supplied by the hearing aid. Within our semantic framework to disentangle spatial release from masking (Dieudonné & Francart, 2018b), we have shown that spatial release from masking can indeed be analyzed as a trade-off between a change in SNR at the CI side due to the head shadow, and a difference in bimodal benefit, mediated by a change in SNR offset at the hearing aid side. There is probably no binaural unmasking involved in this, as represented by binaural contrast that is consistently negative throughout the literature and in our experiments.

C. Clinical relevance

Although it seems quite obvious that the bimodal benefit – and speech understanding altogether – depends on monaural signal-to-noise ratios, we are not aware of an explicit discussion on this in current literature. Instead, speech understanding in complex listening situations is often discussed in terms of complex spatial hearing mechanisms. In particular, squelch is often measured to speculate about these mechanisms. We want to encourage measuring *binaural contrast* instead to investigate the use of binaural cues. Despite that, we do not encourage abandoning the measure squelch completely: if "squelch" can be measured for bimodal listeners, this implies that the hearing aid can deliver a benefit in almost all listening conditions, even when the SNR at the hearing aid side is lower than at the CI side. This strongly supports the use of a hearing aid by CI users. However, to avoid a wrong interpretation of the results, we abandoned the term squelch in our analyses, and referred to a bimodal benefit instead.

To conclude, these results might partly shift the focus and interpretation of bimodal signal processing strategies. While loudness balance (Francart & Mcdermott, 2012; Spirrov et al., 2018) and binaural cue preservation/enhancement (Francart et al., 2011, 2014) are important for listening comfort and sound localization, their influence on speech perception is probably minor. Instead, to improve speech perception, it is the simplest and probably most efficient to focus on monaural sound quality (e.g., audibility, SNR, minimal distortion, etc.) (Wouters et al., 2013). For example, Devocht et al. (2016) have shown that a using a monaural beamformer in the CI improved speech understanding, and a monaural beamformer in the hearing aid entailed an additional (but smaller) benefit in speech understanding for bimodal listeners. These results can simply be explained in terms of monaural signal-to-noise ratios. Veugen et al. (2016a) have shown that changing from a fast to a slow compressor in the hearing aid might improve the bimodal benefit; although improved binaural processing is speculated, the extra benefit might also be due to better monaural sound quality (Stone & Moore, 2003) or long-term signal-to-noise ratio (Wiggins & Seeber, 2013). In our bimodal sound processing strategy to amplify interaural level differences (Dieudonné & Francart, 2018a), improved speech intelligibility could also be explained in terms of monaural signal-to-noise ratios: an improved head shadow benefit if the noise was at the hearing aid side (due to improved SNR at CI side), or an improved bimodal benefit if the noise was at the CI side (due to improved SNR at hearing aid side). Unless there is a very high (unrealistic) amount of informational masking (Bernstein et al., 2015, 2016), or unmasking based on interaural time differences can be achieved somehow, there is probably no significant spatial cue processing involved in the speech understanding for bimodal listeners.

VI. Conclusions

We investigated binaural and spatial effects in speech understanding for bimodal listeners. Based on a semantic framework to unambiguously quantify and relate these effects (Dieudonné & Francart, 2018b), and trends in the performance of bimodal listeners that were reported in previous literature (see **section I.C**), we assert that there is no binaural cue processing involved in their speech understanding, i.e., no binaural unmasking. Instead, speech understanding can be characterized as a simple function of monaural signal-to-noise ratios, or monaural sound quality in general. Our hypothesis was further investigated by two experiments in which we measured speech understanding in simulated bimodal listeners with different masker types (1) in realistic spatial scenarios (with HRTFs), and (2) while adapting the broadband signal-to-noise ratios in both ears independently. To avoid further confusions about binaural speech processing in general, we want to emphasize two guidelines that should be followed in future research:

1. When discussing or quantifying a binaural effect, a proper definition should be given, and an explicit discussion on what the effect involves. For example: *squelch* for bimodal listeners is the benefit of listening with the CI and the hearing aid, as compared to listening with the CI only, when the masker is situated at the hearing aid side and the target is presented in front of the listener. When adding the hearing aid, extra redundant, complementary and

spatial information is made available about both the target and masker. Therefore, squelch is not necessarily the result of binaural cue processing; however, it does imply that the hearing aid delivers a benefit in almost all listening conditions, even when the signal-to-noise ratio at the hearing aid side is lower than at the CI side. To investigate the use of binaural cues in speech understanding, we encourage measuring *binaural contrast*: the difference between SRM and head shadow.

2. While it seems quite obvious that speech understanding depends on monaural signal-to-noise ratios and monaural sound quality, the focus is often on complex binaural cue processing when discussing speech intelligibility in adverse listening conditions. In accordance with the principle of Occam's razor, we advise to first focus on the simplest hypothesis to explain speech understanding performance for different populations or for different sound processing strategies.

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