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The object-related negativity (ORN) component as an objective measure of concurrent sound segregation

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ABSTRACT

Electroencephalography (EEG) is a popular technique for deriving objective measures of auditory function due to its sensitivity to fine details of auditory processing, its high temporal precision, and its applicability across a wide range of participant groups with low testing burden. I will discuss the suitability of a specific EEG measure as a tool for objectively studying the perceptual segregation of concurrent sound sources: namely the object-related negativity (ORN) component of the event-related brain potential (ERP). The ORN component was introduced by Alain and colleagues almost twenty years ago to reflect the perceptual segregation of simultaneous sounds. I will show recent ORN results from healthy young adults and from elderly listeners with slight hearing impairment, indicating high sensitivity of the ORN at group level. I will extend these results towards the question whether ORN is sensitive enough to measure sound segregation abilities at single-subject level. Based on detailed correlation analyses between ORN measurements and perceptual judgments in young and elderly listeners, I will point out promises but also caveats in using the ORN for individual diagnostics of auditory function.

Keywords: sound source separation, electroencephalography (EEG), diagnostics

1. INTRODUCTION

Humans show inter- and intraindividual differences in their auditory processing skills, just like in any other ability. Diagnostic tools for assessing individual auditory processing abilities are valuable in various application scenarios, be it for selecting particularly adept persons as sound engineers or for quantifying the need – and then the success – of providing treatment opportunities (e.g., hearing aids or cochlear implants) to those whose auditory processing abilities fall short of healthy hearing.

An individual's ability to process sounds can be probed at great detail with psychophysical methods. These psychophysical methods can be categorized along various dimensions, including:

- the aspect of auditory processing they target (threshold measurements, supra-threshold comprehension, sound source separation / auditory scene analysis, etc.),
- their efficiency (with adaptive or staircase procedures being more efficient than classical constant-stimulus procedures),
- their objectivity. The *objectivity* term is used somewhat differently across disciplines.

In psychophysics, a subjective method is one where only the listener knows the correct answer: A typical question is "Did you hear a sound?", with the listener replying "Yes" or "No", and with a sound always present. With settings of this type, listeners can pretend to hear better (or worse) than they actually do; and even if the listener has the intent to answer as honestly as possible, the answer will depend on their response criterion (put simply, on their tendency to say "Yes" or "No" when the sensory evidence is ambiguous). To overcome such subjective influences that are unrelated to hearing ability per se, objective psychophysical measurement techniques have been developed. In so-called criterion-free measurements, the experimenter knows the correct answer and hence can validate the listener's response: A typical question is "Was this sound high or low?" The key point of such objective measurement approaches is that a false response is clearly indicative of the listener not having heard the sound, while a correct response is indicative of successful hearing after correction for the guess rate. Alternatively, the question might remain "Did you hear a sound?", but with the twist that no sound is present on some trials (so-called catch trials). In this case, the listener's response criterion can be estimated from the distribution of "Yes" and "No" responses

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across trials with and without sound presentation based on signal detection theory (1). Pure-tone audiometry is still partly based on subjective measurements, whereas modern speech comprehension tests usually employ objective criterion-free measurements (2). Both use staircase procedures nowadays to render testing more efficient and more accurate at the same time.

Besides subjective and objective psychophysical measurements, a third way of assessing sound processing abilities is the use of psychophysiological measurements such as otoacoustic emissions, eyetracking/pupillometry, or electroencephalography (EEG). These measurements have in common that they no longer require an overt response by the listener, as they infer auditory processing abilities from physiological responses to certain sounds. Some authors reserve the term "objective" exclusively for these techniques (3), which is important to acknowledge to avoid terminological confusion across different disciplines. The notion that a physiological measurement is more objective than any psychophysical one mainly stems from the worry that involving listener responses confounds the test result with factors unrelated to hearing ability. Yet a criterion-free psychophysical measurement largely alleviates this problem because "faking good" is impossible since responses can be validated, and "faking bad" is unlikely as it requires a fair amount of knowledge about the testing procedure. Some other factors affecting behavioral responses, such as the amount of attention devoted to the sounds or the task, affect psychophysical and psychophysiological responses alike – at least those psychophysiological responses that are more remote from the initial sensory transduction, such as eye movements and EEG responses elicited by sounds (4).

Nevertheless, for some questions there are undisputable advantages of psychophysiological over (even objective) psychophysical measurements. One of these advantages is the applicability to a range of contexts in which measurements requiring a response by the listener are impossible: Either because the ability to respond is temporarily unavailable (e.g., during sleep or anesthesia), or because it is restricted for longer periods of time (e.g., in neonates or coma patients). Another advantage of psychophysiological measurements lies in the fact that they can assess auditory processing outside the focus of the listener's attention, which greatly reduces the testing burden: Ideally, the listener can engage in an enjoyable activity like watching a sub-titled movie or reading a book (5), while their auditory processing abilities are assessed in the background. This opportunity could be a great relief to hearing-aid or cochlear-implant patients, who otherwise would have to participate in lengthy fitting sessions that involve performing the same listening task over and over again – which can be heavily frustrating for those who are hard of hearing.

Psychophysiological measurements thus have the potential to facilitate auditory diagnostics in a variety of listeners, ranging from sleeping neonates (6) to listeners with severe degrees of hearing impairment for which behavioral testing would present too much of a burden (7). The remainder of this paper focuses on diagnosing higher auditory processing abilities on the basis of EEG, and more specifically, on event-related brain potentials (ERPs) extracted from the listener's continuous EEG recording. ERPs are popular measures of auditory function due to their sensitivity to fine details of auditory processing, their high temporal precision, and their applicability across a wide range of participant groups with low testing burden.

2. AUDITORY CORTICAL EVENT-RELATED BRAIN POTENTIALS

Auditory ERPs are elicited in response to above-threshold sounds. They are usually uncovered by averaging EEG epochs across a certain number (on the order of 100) of stimulus presentations to remove high-amplitude spontaneous brain activity. When adequate signal-to-noise ratio has been reached, ERPs show a characteristic series of deflections, some of which can be directly mapped to stages of auditory function (8). For instance, the brainstem-evoked potentials (auditory brainstem responses, ABRs) and middle-latency responses (MLRs) reflect the bottom-up flow of information through different subcortical and thalamocortical processing stages along the auditory pathway, as well as their modulation by top-down information. Of particular interest for the present work are auditory long-latency responses (LLRs) reflecting auditory information processing in the cortex.

Several long-latency ERP components have been identified that correlate with abilities involved in sound processing. For the present purposes, those ERP components that are elicited automatically (i.e., without any need for the listener to pay attention to the sounds or perform a task on them) are of greatest interest, because they exploit the full potential of psychophysiological measurements – studying listeners who are not able to give behavioral responses, and reducing the testing burden for any listener. Besides the obligatory sensory ERP components P1/P50 and N1, the bulk of work on "automatic" auditory cortical ERPs has employed the mismatch negativity (MMN) component.

MMN is elicited when the auditory system detects an unexpected sound – usually a rare sound amongst a series of frequent sounds (9). This, in turn, can be used to probe the listener's ability to make certain acoustic distinctions, since detecting the rarity of a sound is only possible if the listener can perceive the difference between rare and frequent sounds. Depending on the attribute defining the rarity, MMN can be employed to probe the listener's accuracy in physical feature discrimination, their ability to extract complex regularities (patterns) between successive sounds, or their sequential auditory scene analysis abilities in situations with more than two putative sound streams. These wide-spread options, together with its ease of application, have made the MMN component a popular tool for tapping into auditory processing. A large body of work is now available showing the utility of MMN-based measurements across a wide range of research questions at group level (e.g., 6, 7, 10,11). There are also many successful extensions to diagnostic questions at single-subject level (e.g., 3, 12). One remaining challenge of MMN-based diagnostics is the small amplitude of the component, requiring a large number of trials to achieve sufficient signal-to-noise ratio. This poses a particular challenge because MMN paradigms crucially depend on the rarity of the eliciting stimulus: increasing the frequency of the rare stimulus unavoidably reduces MMN amplitude. The optimum frequency has been estimated at 8-10% (13), leading to the requirement to present ten times more stimuli than the one of interest. One important optimization of the MMN paradigm involves presenting many different types of physical feature changes in one sequence (14), which makes the paradigm much more efficient – yet it does not affect the challenge that the overall frequency of each physical feature change should not exceed 10%. Hence long data collection times are required.

Almost twenty years ago, the work by Claude Alain and colleagues (15) has brought another auditory ERP component onto the picture: the so-called object-related negativity (ORN). The ORN component is elicited when simultaneous sounds are perceived as originating from two separate sound sources. This perceptual process is called concurrent sound segregation, and the ORN reflects either the process itself or its result: the perception of two or more sounds in a mixture. The ORN inherited its name (i.e., object-related negativity) from the fact that the decomposition of a sound mixture into its constituent parts is also called auditory object formation.

Unlike the MMN, the ORN is largely independent of the eliciting event's probability (16, but see 17). Surprisingly, compared to the MMN, the ORN has received a considerably smaller amount of research attention; in fact, its potential as a diagnostic tool of auditory function might be greatly underestimated. The remainder of this paper discusses the suitability of the ORN as a tool for objectively studying the perceptual segregation of concurrent sound sources at group level as well as at single-subject level (i.e., for individual diagnostics).

3. EMPIRICAL WORK ON ORN & CONCURRENT SOUND SEGREGATION

3.1 ORN-based measurements at group level

Alain and colleagues introduced the ORN as an ERP correlate of concurrent sound segregation (15). ORN is elicited by many different cues inducing perceptual segregation of simultaneous sounds such as inharmonicity (15), dichotic pitch (16), simulated echo (18), differences or discontinuities in location (19), and onset asynchrony (20, 21, see Figure 1).

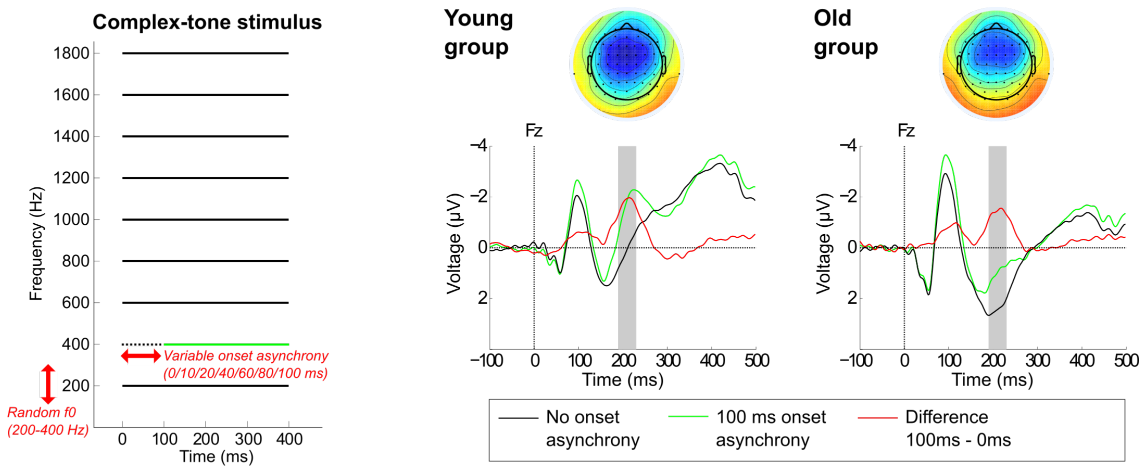

Figure 1 – Stimulus (left) and ORN results (right) of sound segregation based on onset asynchrony

For instance, a study in our lab (21) investigated the segregation of simultaneous sounds based on small amounts of onset asynchrony between them. Harmonic tone complexes were presented with the second partial being delayed within a range of 0 to 100 ms. This mimics the fact that even when two independent sound sources emit sounds concurrently, it hardly ever happens that they start producing sounds at exactly the same time. The processing of onset asynchrony as a cue for concurrent sound segregation was compared between young, normal-hearing listeners (N=20, ∅26 years) and elderly listeners with mild hearing impairment (N=18, ∅65 years).

Stimulus configuration and ORN results are displayed in Figure 1. ORN was calculated by subtracting ERPs elicited by stimuli without onset asynchrony from those with onset asynchrony. Similar to the better-known MMN, the ORN presents as a frontocentral negativity with polarity inversion at the mastoid electrodes when nose reference is used. This is consistent with generators in the auditory cortex (15, 22). ORN latency, amplitude, and topography were all highly similar in the two age groups, as displayed on Figure 1 for the highest amount of onset asynchrony that was investigated – the same was true for all other levels of onset asynchrony as well. ORN amplitude increased with onset asynchrony ($p<.001$) independently of age group. Figure 2 illustrates this for ORN amplitude at a frontocentral electrode (Fz) and at the average of the mastoid electrodes (CM). The apparent similarity and statistical indistinguishability of the two age groups suggests that concurrent sound segregation by onset asynchrony is preserved in healthy auditory aging (21).

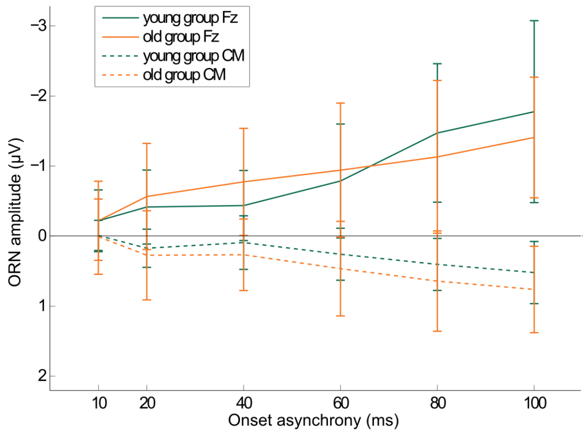

Figure 2 – ORN amplitude as a function of group and onset asynchrony at Fz and Common Mastoids (CM)

These results were confirmed in an independent study on new samples of young and elderly listeners, using speech sounds rather than complex tones, with the same manipulation of onset asynchrony (23). Again, both age groups benefitted to a similar extent from using onset asynchrony for concurrent sound segregation. This contrasts other segregation cues like inharmonicity, whose use has been shown to decline with age (24). Such findings are informative for models of concurrent sound segregation, for hearing training programs, and for hearing aid design.

Regarding the core conclusion that the ability to segregate concurrent sounds by onset asynchrony is relatively preserved in older listeners, in both studies (21, 23) the ORN results obtained during passive listening were well in line with the results of psychophysical testing during active listening. For the harmonic tone complexes displayed in Figure 1, active listening consisted in a threshold measurement regarding the sound level at which the delayed partial must be presented for the listener to hear two concurrent sounds. Elderly listeners showed generally lower performance in this task, which was evident in the condition without onset asynchrony and was carried through all conditions with onset asynchrony. Importantly, the elderly listeners' performance increase across the different onset asynchrony levels was identical to that of the young listeners. This corresponds to ORN amplitudes being indistinguishable between the age groups, since ORN directly reflects the difference of conditions with versus without onset asynchrony. This correspondence of EEG and behavioral data suggests that the ORN component is a valuable tool to complement or even replace psychophysical testing in cases where behavioral measurements are impossible or present too much of a burden. The successful application of ORN for group-level investigations naturally leads to the question whether it might be suitable for individual diagnostics. An extension to the purposes of individual diagnostics, however, requires revisiting the results at the single-subject level.

3.2 ORN-based measurements at single-subject level

Similar to the onset asynchrony study shown in Section 3.1 (21), group-level investigations have demonstrated that the ORN is elicited by a great variety of cues inducing concurrent sound segregation (15, 16, 18, 19, 20). In turn, the ORN could be used to measure the integrity of the processing of each of these cues in the auditory system of an individual listener for diagnostic purposes. This possibility has been explored in some studies regarding age-related changes (25), effects of musicianship (26), and changes in auditory processing of persons diagnosed with autism-spectrum disorder (27). In contrast, it has not received much attention as an auxiliary diagnostic tool for listeners with hearing loss, such as for fitting or follow-up success control of hearing aids or cochlear implants – MMN seems to be considered the key EEG indicator in those cases (28). Similar to the MMN, ORN can be recorded outside the focus of attention and thus offers a low-burden measurement for individual patients. It also lends itself towards investigations in populations in which behavioral testing is difficult or impossible, such as in pre-verbal infants.

Yet the transition from the group level to the individual level requires careful examination of several prerequisites: Is the ORN sensitive enough to measure sound segregation abilities at the level of a single listener? Does it show adequate test-retest reliability? Does the strong relation between the amount of physical feature change and the ORN amplitude (Figure 2) hold at the individual level? Do single-subject ORN amplitudes correlate highly with behavioral testing scores, such that it is feasible to replace psychophysical with psychophysiological measurements in this case?

We were able to address some of these questions in our study outlined in Section 3.1 on onset-asynchrony-based segregation of concurrent sounds in young and elderly adults (21). Figure 3 shows the results of correlation analyses between psychophysiological data (ORN amplitude; with more negative values indicating better processing of the cue) and psychophysical data (behavioral threshold improvement for hearing the delayed partial; again with more negative values indicating better performance).

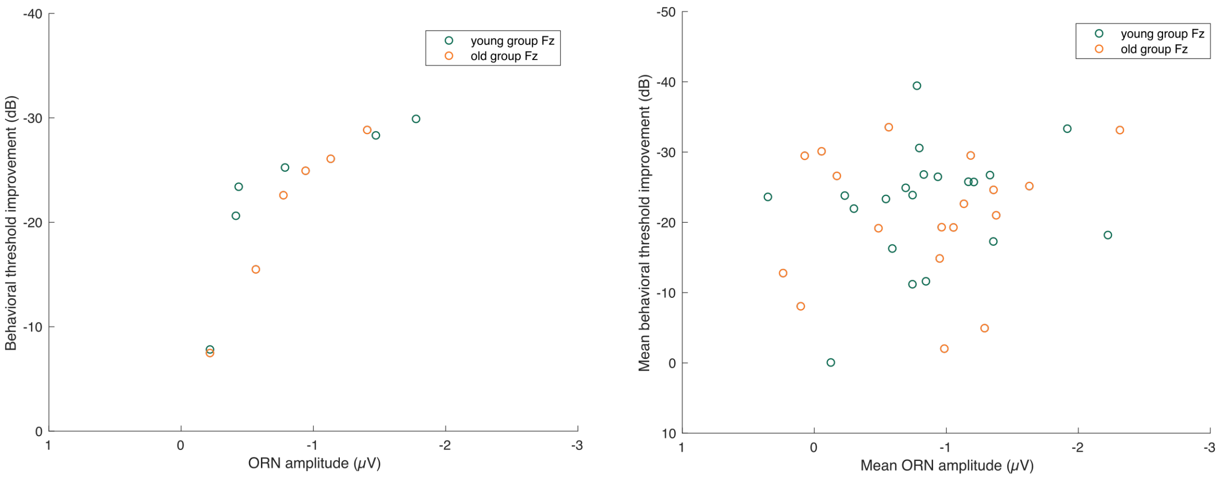

Figure 3 – Relation of EEG and behavioral data within listeners (left) and across listeners (right)

The left panel of Figure 3 shows a scatter plot of the group-level relation between ORN amplitude at Fz and behavioral threshold improvement within listeners, separately for each age group (young in green, elderly in orange). ORN amplitude and behavioral threshold improvement were averaged across listeners separately for each onset asynchrony level, yielding six scores (10/20/40/60/80/100 ms) for each of the two measures (behavioral threshold improvement/ORN amplitude). Each circle thus indicates one onset asynchrony condition. Pearson correlation between ORN amplitude and behavioral threshold improvement was significant for the whole sample ($r=.878$, $p<.05$), and was numerically even higher in the elderly group ($r=.962$, $p<.01$) than in the young group ($r<.794$, $p=.059$). Hence, at group level, the elicitation of higher (more negative) ORN amplitudes in a given condition (onset asynchrony level) was associated with larger performance improvements in detecting the delayed partial (i.e., the delayed partial could be detected at lower sound levels).

The good correspondence between EEG and behavioral data might be suggestive of the conclusion that the two approaches measure similar aspects of concurrent sound segregation by onset asynchrony, and hence that one could replace the other. However, when the aim is individual diagnostics, showing strong correlation at group level is not sufficient: The relation might be much weaker in the individual datasets simply due to reduced signal-to-noise ratio. Hence the correlation must be revisited at the single-subject level. This is possible by recomputing the correlation of ORN amplitude and behavioral threshold improvement for each listener, yielding 38 individual correlation scores. In order to assess whether the single-subject correlations exceed chance level, the average individual correlation can be tested against zero by applying Fisher's z transformation. The group-average z value was 0.661, corresponding to a back-transformed average correlation of 0.579, which was significantly higher than zero ($p<.001$). Again, results were highly similar when analyzed separately within each age group (young listeners: $z=0.602$, back-transformed $r=0.539$, $p<.001$; elderly listeners: $z=0.726$, back-transformed $r=0.621$, $p<.001$). This implies that, within the majority of the listeners, a higher (more negative) ORN amplitude in a given condition (onset asynchrony level) was associated with higher behavioral threshold improvement in this condition. The reduction of the single-subject correlation ($r=.579$) relative to the group-level correlation ($r=.878$) is well in line with previous studies (25, 26); the amount of reduction is tied to the signal-to-noise ratio in the individual data. In the current case, signal-to-noise ratio and thus sensitivity of the measurement was apparently sufficient at single-subject level.

It is important to realize that these correlations were conducted *within* each listener *across* onset asynchrony levels. Therefore, they permit the following conclusion: If a listener shows a higher ORN amplitude in condition 1 than in condition 2, that same listener will tend to also show a higher behavioral threshold improvement in condition 1 than in condition 2. This conclusion is beneficial when drawing comparisons across conditions (e.g., different stimuli, or different ways to present these stimuli, such as in different preprocessing settings of a hearing aid). It must not be confused with a possible relation between EEG and behavior *across* listeners. In other words, it does *not* allow for the following conclusion: If listener A shows higher ORN amplitude than listener B, listener A will tend to also show a higher behavioral threshold improvement than listener B. This issue must be tested in a different way as follows.

The right panel of Figure 3 shows a scatter plot of the single-level relation between ORN amplitude at Fz and behavioral threshold improvement across listeners, separately for each age group (young in green and elderly in orange). ORN amplitude and behavioral threshold improvement were averaged across onset asynchrony levels separately for each listener, yielding 38 scores for each of the two measures (behavioral threshold improvement/ORN amplitude). Each circle thus indicates one listener. In contrast to the analyses above, Pearson correlation between ORN amplitude and behavioral threshold improvement was not significant across the whole sample ($r=.181$, $p=.277$), nor was it significant within either age group (young listeners: $r=.232$, $p=.324$; elderly listeners: $r=.136$, $p=.591$). Hence a listener with higher (more negative) average ORN amplitudes did not necessarily have larger average performance improvements in detecting the delayed partial – in other words, mean ORN amplitude of a listener could *not* be used as a proxy for mean behavioral threshold improvement of the same listener.

The patterns of each of these correlation analyses was highly similar to those obtained in our parallel study (23) employing the same manipulation with speech sounds. Together, the results suggest that direct inference from ORN amplitude on behavioral measures (and vice versa) is feasible when comparing different conditions within each group or within each listener, but *not* feasible when comparing different groups or different listeners with each other. This is not a matter of excessive noise in the individual data: The correlation within listeners (left panel of Figure 3) was significant both at group level and at single-subject level. The sensitivity of the measurement (including its signal-to-noise ratio) was thus adequate.

It should be emphasized that the specific correlation pattern presented here was obtained for this particular context (i.e., comparing the processing of onset asynchrony in young and mildly hearing-impaired elderly listeners) – in other contexts, correlations of ORN amplitude and behavioral scores across listeners have indeed been reported (27). Hence a general recommendation is that the different levels of making comparisons (within or across listeners) should not be confused with one another, and that the validity of equating psychophysiological with psychophysical data must be tested in each specific context.

3.3 Promises and caveats

Based on the work presented in the above sections, complementing or even replacing psychophysical by psychophysiological (ORN-based) testing is highly promising for certain research and applied questions. In the context of fitting a hearing-assistive device (i.e., testing different settings against each other) or evaluating its success (reassessing hearing ability in longitudinal follow-ups), the lack of correlation across listeners does not matter because the correlation within listeners gives the necessary piece of information: Higher ORN amplitude of a listener with setting 2 than with setting 1 implies that this listener is likely to show a larger perceptual benefit from setting 2 than setting 1. Higher ORN amplitude of a listener at time-point 2 than at time-point 1 implies that this listener's perception likely has also improved. Hence, psychophysiological data gives exactly what is needed to make a choice for the listener's benefit. It can be recorded with low testing burden (mainly the application of the electrodes; the testing itself can be done outside the focus of attention, while the listener engages in an enjoyable activity like watching a video). This alleviates some of the frustration involved in running many different psychophysical tests in listeners who are hard of hearing. At the same time, ORN-based testing has high face validity for the listener: The situation that two sounds are overlapping and must be disentangled is one that any listener frequently encounters in daily life, and a situation that many hearing-impaired listeners struggle with.

Of course, many questions still need to be addressed before applying the ORN in a routine manner. An important question concerns the number of stimulus presentations needed to achieve acceptable accuracy and reliability of the measurement. (It is worthy to note that this is an open question for other components as well, even if they are already routinely applied.) One beneficial aspect of the ORN is that increasing the stimulus number does not come with a large overhead because component amplitude is largely independent of overall stimulus probability (16, but see 17).

One note of caution is needed regarding the interpretation of the ORN as a correlate of perceptual segregation. In the study presented in Sections 3.1. and 3.2 (21), the ORN could equally well be a simple response to the physical difference between the synchronous and asynchronous sounds (e.g., an N1 component elicited by the delayed part of the sound). This caveat applies to many other ORN studies as well, because the stimuli leading to perceptual segregation typically differ in physical terms from the stimuli perceived as a unitary sound. However, there is some evidence that ORN elicitation matches perception with physically identical stimuli that can be interpreted as one or two sounds (18). Moreover, even if the ORN turns out to be dominated by physical rather than perceptual factors, its elicitation still speaks to the integrity of processing this particular physical difference (cue) in the listener's auditory system. For many applied questions, this is fully sufficient, whereas whether the response reflects mere cue processing or higher-level object formation is not a key issue. What would be more important from an applied point of view, is to study whether ORN elicitation is predictive of being able to use the eliciting cue in real-life auditory scene analysis.

4. CONCLUSIONS

Starting from some general considerations about the utility of psychophysiological measurements for studying auditory function, this paper introduced the notion that the ORN component should be explored more widely in this context. Despite some caveats and outstanding issues, this component seems to bears great promise for diagnosing an individual's ability to segregate concurrent sound sources, and to process the acoustic cues that are needed therein. The ORN component may have the potential to become a routine tool for evaluations in the context of hearing-assistive devices.

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