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Research Paper

Electric-acoustic forward masking in cochlear implant users with ipsilateral residual hearing

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ABSTRACT

In order to investigate the temporal mechanisms of the auditory system, psychophysical forward masking experiments were conducted in cochlear implant users who had preserved acoustic hearing in the ipsilateral ear. This unique electric-acoustic stimulation (EAS) population allowed the measurement of threshold recovery functions for acoustic or electric probes in the presence of electric or acoustic maskers, respectively. In the electric masking experiment, the forward masked threshold elevation of acoustic probes was measured as a function of the time interval after the offset of the electric masker, i.e. the masker-to-probe interval (MPI). In the acoustic masking experiment, the forward masked threshold elevation of electric probe stimuli was investigated under the influence of a preceding acoustic masker. Since electric pulse trains directly stimulate the auditory nerve, this novel experimental setup allowed the acoustic adaptation properties (attributed to the physiology of the hair cells) to be differentiated from the subsequent processing by more central mechanisms along the auditory pathway. For instance, forward electric masking patterns should result more from the auditory-nerve response to electrical stimulation, while forward acoustic masking patterns should primarily be the result of the recovery from adaptation at the hair-cell neuron interface.

Electric masking showed prolonged threshold elevation of acoustic probes, which depended significantly on the masker-to-probe interval. Additionally, threshold elevation was significantly dependent on the similarity between acoustic stimulus frequency and electric place frequency, the electric-acoustic frequency difference (EAFD). Acoustic masking showed a reduced, but statistically significant effect of electric threshold elevation, which did not significantly depend on MPI. Lastly, acoustic masking showed longer decay times than electric masking and a reduced dependency on EAFD.

In conclusion, the forward masking patterns observed for combined electric-acoustic stimulation provide further insights into the temporal mechanisms of the auditory system. For instance, the asymmetry in the amount of threshold elevation, the dependency on EAFD and the time constants for the recovery functions of acoustic and electric masking all indicate that there must be several processes with different latencies (e.g. neural adaptation, depression of spontaneous activity, efferent systems) that are involved in forward masking recovery functions.

1. Introduction

Forward masking is a result of the presence of one stimulus which reduces the detectability of a following stimulus. Forward masking has been investigated and characterized in both normal and impaired acoustic hearing subjects (Nelson and Freyman, 1987) as well as in electric hearing with cochlear or midbrain implantees (McKay et al., 2013). The goal of this work is to report on forward masking effects across acoustic and electric hearing in the same ear

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Abbreviations

CAP	compound action potential
CBCT	cone beam computer tomography
CI	cochlear implant
DR	dynamic range
EAFD	electric-acoustic frequency difference
EAS	electric-acoustic system
El	electrode
MCL	most comfortable level
MPI	masker-to-probe interval
pps	pulses per second
TE	threshold elevation
THL	threshold level

in humans.

Acoustic forward masking studies have used an exponential decay model of forward masking threshold elevation, which has been described by different time constants for normal hearing (40–50 ms, Nelson and Pavlov, 1989) and hearing impaired subjects (60–110 ms, Nelson and Freyman, 1987). Different mechanisms have been proposed to explain this exponential decay of probe threshold elevation. Short-term inhibition has been argued to be the basis of firing rate decrease of the auditory nerve (Smith, 1977), as adaptation is not found at the stage of the hair cell itself (Davis, 1957; Mulroy et al., 1974). Correspondingly, a model has been developed that includes adaptation at the stage of the auditory periphery through the depletion of transmitter substance, which accounts for forward masking effects (Duifhuis and Bezemer, 1983). Further exponential models of neural-synaptic-recovery mechanisms have been described, which correspond well to data of hearing-impaired listeners with sensorineural hearing loss at the probe frequency (Nelson and Pavlov, 1989). However, concurrent to computational models of synaptic adaption (Meddis and O'Mard, 2005), models have been defined that combine the peripheral mechanical nonlinearities of the basilar membrane with a linear temporal integration at higher levels (Oxenham, 2001). The latter model also explains well the experimental outcomes but still does not rule out synaptic adaptation completely.

Forward masking has also been reported in cochlear implants (Shannon, 1983). The observed masking patterns have been used to investigate spatial characteristics of electrical field spread (Boëx et al., 2003; Hughes and Stille, 2008; Kwon and van den Honert, 2006) and to develop an artifact reduction algorithm for electrophysiological measurements (Cohen et al., 2003). At first, these forward masking effects were unexpected, since cochlear implants bypass both basilar membrane nonlinearities and hair cell functionality (Lim et al., 1989). However, exponential decay functions are used to describe forward masking recovery functions for electric hearing (Shannon, 1990). Further studies have reported time constants of exponential recovery functions in electric hearing that vary strongly (e.g. 25–160 ms, Nelson and Donaldson, 2002) or that are greater than time constants for acoustic forward masking (Shannon, 1983). This is attributed to an increased adaptation due to the high firing rate an electric stimulus elicits in the auditory nerve (Harris and Dallos, 1979). These results indicate that the origins of electric masking are different from the origins of acoustic masking. Electric forward masking patterns warrant the conclusion that peripheral cochlear functions are not solely responsible for temporal mechanisms of masking. Several following studies confirm forward masking through electric stimulation of the auditory nerve with CIs (Chatterjee, 1999; Nelson and Donaldson, 2002) and of the inferior colliculus with auditory midbrain implants (McKay et al., 2013).

In electric-acoustic stimulation (EAS) users, both modalities are combined in one ear. As described above, electric and acoustic stimulation excite different stages of the auditory pathway with different temporal characteristics. However, recent studies have found electric-acoustic masking effects during simultaneous presentation (Lin et al., 2011; Saoji et al., 2017). Furthermore, an asymmetry between electric and acoustic masking exists, with electric maskers producing a pronounced threshold elevation of acoustic probes that depends strongly on the electric-acoustic frequency difference (EAFD), while, at the same time, these effects are reduced for acoustic maskers (Krüger et al., 2017). Additionally, peripheral electrophysiological measurements have been applied to objectively estimate electric-acoustic interactions during simultaneous stimulation (Koka and Litvak, 2017). Thus it has proven necessary to investigate non-simultaneous masking effects in order to study the temporal mechanisms of electric-acoustic interaction. The present study therefore examined for the first time psychophysical temporal masking effects in EAS users using a forward masking paradigm. This opportunity to gain insights into the auditory pathway would not have been possible prior to CIs.

In this work, the EAS subjects represent a unique population of cochlear implantees with residual hearing in the ipsilateral ear. As more and more CI users retain a significant amount of residual hearing after cochlear implantation, temporal electric-acoustic masking effects might be occurring in EAS users. Advances in surgical techniques (Gantz and Turner, 2004; Gstoettner et al., 2004) and softer electrode designs (Lenarz et al., 2009; Suhling et al., 2016) during the past decade lead to successful hearing preservation, resulting in an increasing proportion of the CI population benefiting from EAS. This resulted in an extension of CI criteria towards patients with more residual hearing (Skarzynski et al., 2007). Consequently masking effects may become clinically relevant, but to this day commercial EAS devices do not incorporate a synchronization or exchange of information between electric and acoustic components. Presently, the EAS subject population was small, but offered the unique opportunity to investigate electric-acoustic interaction effects in order to better understand mechanisms of auditory processing.

Forward masking was investigated using a novel electric-acoustic forward masking paradigm. The threshold of a short signal was measured at a certain interval after the offset of a masker stimulus of the opposing modality. The increase in threshold necessary to perceive the probe was analyzed as a function of the masker-to-probe interval (MPI). This curve was called a forward-masking recovery function. The strength and asymmetry of forward masking was compared to the observations of simultaneous electric-acoustic masking in humans and to physiological animal studies. Despite the fact that physiological animal studies yield insights into auditory processing during electric-acoustic stimulation, no clear consensus exists on the different origins of forward masking. The forward masking paradigm was used to compare the temporal integration mechanisms of auditory processing for electric and acoustic hearing and thus to differentiate components of the peripheral and central pathways.

2. Methods

2.1. Subjects

Ten EAS users participated in this study. Seven were implanted with the MED-EL Flex20, one with a Flex24 electrode array and two with the Hannover custom made device Flex16. Numbers denote the length of the electrode array in millimeters. All subjects had

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