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Associations of the Medial Olivocochlear Reflex and Speech-In-Noise Abilities in Normal Hearing Adult Listeners: A Systematic Review

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by
IMARI GREAVES

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Abstract

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IMARI GREAVES

Advisor: John Preece, Ph.D

This systematic review analyzed the research concerning the medial olivocochlear reflex (MOCR) and speech-in-noise abilities in normal hearing adult listeners. In an attempt to understand the underlying difficulties in this population, the following research questions were proposed: 1) Does the research indicate that the magnitude of MOC suppression measured via OAEs is related to a normal hearing subject's ability to recognize speech-in-noise? 2) Are MOC effects measured via OAEs lateralized? Is there a right ear advantage as suggested by Khalfa, Morlet, Micheyl, Morgon & Collet (1997)? Ten studies met the standards for inclusion for this review. Analysis of the research revealed some involvement of the MOCR in speech-in-noise abilities. However, the studies were mixed in their findings. Several studies did not find substantial correlations while others found significant favorable correlations. Interestingly, all of the studies that utilized speech-in-noise tests with words as the target stimuli found better speech recognition performance with increased MOC activity. In regards to laterality, the studies did not all point to a clear right ear advantage. The variability of the findings does not dampen the promise of potential clinical applications. Instead, they lay the groundwork for future controlled experiments that can confirm the involvement of MOCR in the discrimination of speech in the presence of background noise.

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Most importantly, I would like to dedicate this paper to my grandparents, Leslie, Louise, James & Delrose, and my parents. Thank you all for having the courage to immigrate to the United States from Jamaica and instilling me with a deep love of education. I am forever indebted and will continue to live by the sentiments this mantra:

> Opportunity a scarce, scarce commodity
> In these times I say
> When mama spend her last and send you go class
> Never you ever play…
>
> Banton, B. (1995). Untold Stories. On '*Til Shiloh.* Island Records.

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Introduction

Speech-in-Noise

Listening to speech in the presence of background noise is often challenging, even for individuals with normal hearing. In fact, results from the Beaver Dam Offspring Study (Tremblay et al., 2015), indicated that 12% of individuals with normal audiometric thresholds identify as having hearing difficulties, marked by problems hearing speech in noisy situations. Hind, Haines-Bazrafshan, Benton, Brassington, Towle, B & Moore (2011), determined that 4% of young adults referred to audiology services for listening difficulties have clinically normal audiograms. These cases of normal hearing individuals with perceptual difficulties of listening to speech-in-noise challenges audiologists and researchers to determine potential causes of this phenomenon and develop effective clinical treatments for patients.

A wide variety of etiologies have been theorized to be responsible for perceived difficulties listening to speech in a noisy environment. Possible audiologic causes include cochlear synaptopathy (Kujawa & Liberman, 2015), King-Kopetzky syndrome (Zhao & Stephens, 1996) and central auditory processing disorders (Bellis & Ferre, 1999). Nevertheless, the root of many of these concepts include the role of the efferent system.

Efferent System: Anatomy

Numerous physiological mechanisms within the human auditory system allow a listener to actively understand speech in noisy situations, one being the efferent system. The efferent pathway, which transmits auditory information from the brainstem to the cochlea, originates primarily from the superior olivary complex. The superior olivary complex is comprised of the medial nucleus of the trapezoid body, the lateral superior olive (LSO) and the medial superior olive (MSO). The latter two nucleus groups are the origin of fibers called lateral olivocochlear (LOC) and the medial olivocochlear (MOC) efferents respectively (Hayes, Ding, Salvi, & Allman, 2013). The LOC arises from the lateral portion of the superior olivary complex and consists of thin, unmyelinated and uncrossed fibers. These fibers emerge from the ipsilateral side of the brain, and course through the vestibular nerve. The majority of these fibers terminate on the ipsilateral primary auditory neurons of the inner hair cells, while a minority terminate on the contralateral cochlear nucleus (Pickles, 2012). The exact function of the LOC remains mostly unknown. It has been suggested that the LOC plays a role in feedback with sound localization based on interaural level differences Darrow, Maison & Liberman, 2006). However, the lack of myelination of LOC fibers makes them challenging to stimulate and more problematic for researchers to explore (Guinan, 2006).

In comparison, the MOC is composed of thick, myelinated and crossed nerve fibers. These fibers arise from the medial portion of the superior olivary complex and desiccate at the fourth ventricle to synapse at the axons of outer hair cells of the contralateral cochlea (Pickles, 2012). A smaller proportion of MOC fibers innervate the outer hair cells of the ipsilateral cochlea. The MOC fibers have narrow tuning curves and innervate the cochlea in a tonotopic fashion (Winslow & Sachs, 1987). The myelination of the MOC fibers allows for more accessible analysis using both electrical and acoustic stimulation (Pickles, 2012). The termination of the MOC fibers at the outer hair cells has led researchers to believe that these fibers have a direct influence on the mechanical properties of the outer hair cells.

Medial Olivocochlear Reflex

Acoustic activation of the MOC efferents is known as the medial olivocochlear reflex (MOCR) (Zhao & Dhar, 2012). When MOC efferents are activated, the active mechanism of outer hair cell movement is restricted, cochlear amplifier gain is reduced, and motility of the basilar membrane vibration is restricted (Cooper & Guinian, 2006). MOC fibers have marginally wider tuning curves compared to cochlear afferent fibers (Lilaonitkul & Guinan, 2009). This action provides frequency specific feedback to a narrow region of the basilar membrane near the characteristic frequency of the acoustic elicitor (Winslow and Sachs 1987).

The MOCR can occur with both ipsilateral and contralateral stimulation. The ipsilateral MOCR acts on the ipsilateral cochlea by way of the ipsilateral auditory nerve and ipsilateral posteroventral cochlear nucleus, which crosses midline at the brainstem to contralateral MOC neurons. These contralateral MOC neurons travel to the ipsilateral cochlea in the crossed olivocochlear bundle. Therefore, ipsilateral MOC reflex is a double-crossed reflex as it crosses the trapezoid body with crossed MOC fibers (Guinan 2006).

The primary and more studied MOCR pathway occurs contralaterally. The contralateral pathway begins with the contralateral cochlea and contralateral auditory nerve fibers that synapse to the neurons of the contralateral posteroventral cochlear nucleus. At the brainstem, the neurons crossover to MOC neurons on the ipsilateral (opposite) side. Unlike the ipsilateral reflex, the contralateral reflex innervates the ipsilateral cochlea through the uncrossed olivocochlear bundle (Guinan 2006). Figure 1 depicts the ipsilateral and contralateral MOCR pathway. The ipsilateral and contralateral MOCR do not vary significantly in the strength of their action (Guinan 2006). However, the measurement of the ipsilateral MOCR can be challenging to obtain due to contamination of the acoustic interactions between the stimulus and the recording (Lilaonitkul & Guinan, 2009). Therefore, the contralateral MOCR reflex is researched more often through the use of otoacoustic emissions.

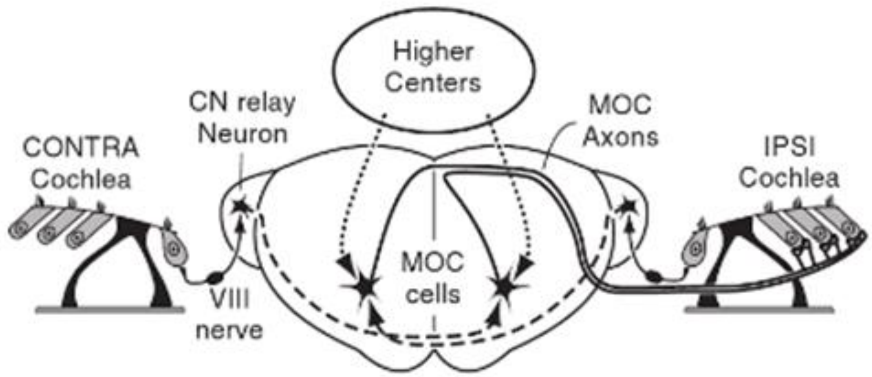

Figure 1: Visual illustration of MOCR pathway. Adapted from: Ryugo, Fay, & Popper, (2010).

Proposed Functions

The MOC system has a largely inhibitory effect. The inhibitory nature of the MOC is thought to protect the inner ear from acoustic trauma, reduce permeant threshold shift (Kujawa & Liberman, 1997) and assist in selective attention (Maison, Micheyl, & Collet, 2001).

The principal role of MOC efferents in humans is believed to minimize uncertainty of transient signals embedded in low level background noise (Guinan 2006), which is known as "antimasking" or "unmasking". In essence, the MOCR is responsible for reducing the auditory system's response to ongoing background stimuli and optimizing responses of transient stimuli. The MOCR hyperpolarizes OHCs, lowers cochlear sensitivity and frequency tuning by decreasing the motility of the cochlear outer hair cell responses (Warren & Liberman, 1989). This overall reduction of response in the presence of continuous noise decreases adaptation at the level of the inner hair cell and auditory nerve fiber synapse and extends the firing range of both a single auditory nerve fiber and the compound action potential (Lilaonitkul & Guinan, 2009). The resulting increased neural output is thought to allow enhanced discriminability of novel stimuli and discernment of changes a target sound (Kawase, Delgutte, & Liberman, 1993). However, the role of MOCR in more complex stimuli, like speech, in noise is still unclear.

Otoacoustic Emissions and Contralateral Suppression

Evidence of MOCR activation has been observed with the use of otoacoustic emissions (OAEs). OAEs are low-intensity sounds created by cochlear outer hair cells that can be measured in the ear canal by a microphone. OAEs can exist spontaneously or can be elicited by sound stimuli. OAE responses reflect the nonlinear mechanism of the cochlea and are dependent upon the normal functioning of the cochlear transduction process (Kemp, 1978) and normal middle ear status.

Spontaneous OAEs (SFOAEs) occur without any acoustic simulation and are present in about 30-40% of healthy ears (Kemp, 2002). They are not typically used for diagnostic purposes. Transient evoked otoacoustic emissions (TEOAEs) and distortion product otoacoustic emissions (DPOAEs) are two evoked types of OAEs that are used to examine the functionality of the active cochlear outer hair cells via differing methods. TEOAE utilizes a brief acoustic stimulus in the form of a click, which encompasses a wide frequency range. TEOAE responses are expected to be present in almost all individuals with normal hearing (Robinette, 2003). Individuals with mild hearing loss or higher and a small sub-section of normal hearing individuals have absent responses. DPOAE utilizes two pure tones with different frequencies (f1+f2) as a stimulus to generate a response from the cochlea. This response, called the distortion product, is a sound that is not present in the input signal. The response is frequency specific and corresponds with particular regions of the tonotopic outer hair cells. DPOAE responses are not expected to be robust or present in individuals with moderate hearing loss or greater than 60 dB HL across frequencies (Gorga et al., 1997). The signal-to-noise ratios of TEOAEs and DPOAEs both indicate the magnitude of active cochlear amplification mechanisms, through different actions. Both TEOAEs and DPOAEs are currently used clinically to supplement the diagnosis of hearing loss, screen hearing in newborns, and monitor ototoxicity-induced hearing loss.

The elicitation of the MOCR hyperpolarizes cochlear outer hair cells and causes inhibition in motility. The reduction in cochlear amplifier gain is recorded as a decrease in OAE amplitude. This phenomenon is known as otoacoustic emission suppression. According to Guinan (2010), the widely utilized term “suppression,” is a misnomer because the reduction in OAE amplitude is mainly due MOC synaptic effects, instead of two-tone suppression as the name might suggest. Nevertheless, OAE suppression that occurs with auditory stimulation of the cochlea is primarily used to assess MOCR function.

Generally speaking, researchers record OAE suppression by presenting stimuli, such as broadband noise or white noise to the ipsilateral ear, contralateral ear or bilaterally. Researchers tend to opt for measuring contralateral suppression since stimulus and the suppressor are separate which would eliminate unwanted acoustic interaction that could occur with ipsilateral measurement. To obtain measurements contralaterally, the conventional protocol involves presenting a stimulus, such as a click or a tone, to the test ear while broadband noise is presented simultaneously to the contralateral ear (Dewey & Dhar, 2012). The difference in OAE amplitude throughout the onset and duration of contralateral noise, compared to the absence of contralateral noise determines the amount of OAE suppression (Brashears, Morlet, Berlin & Hood, 2003). The MOCR measured contralaterally has been noted to be greatest at frequencies under 4000Hz and can range from 0.3–6.5 dB of suppression for TEOAEs (Goodman, Mertes, Lewis, & Weissbeck, 2013) and 0.3-2.7 dB suppression for DPOAEs (Bassim, Miller, Buss, & Smith, 2003).

Middle Ear Muscle Reflex

A likely confound in measuring the MOCR in humans is simultaneous elicitation of the middle-ear muscle reflex (MEMR). The middle ear reflex has both ipsilateral and contralateral pathways, which as the name suggests, causes a contraction of the middle ear muscles. At relatively high-intensity sound levels, contraction of the stapedius muscle stiffens the ossicular chain and causes an increase in impedance, therefore reducing sound propagation. This effect occurs typically with low-frequency signals (Møller, 1962). The MEMR's response to acoustic stimuli occurs between 25–250 ms as compared to the MOC reflex response time of 8–10 ms (Berlin et al., 1993). However, it can be challenging to interpret MOCR findings without first evaluating individuals MEMR threshold, as the two reflexes can produce a reduction in OAE response when activated by contralateral acoustic stimulation (Henin, Long, & Thompson, 2014).

Laterality of the MOCR

Asymmetries occur throughout the human auditory system. Centrally, the right and left hemispheres at the level of the primary auditory cortex are thought to have distinct, yet complementary functions. The left hemisphere is cited to be better for speech discrimination, as there is higher processing of temporal changes, while the right hemisphere better processes changes in frequency for optimal spectral discrimination (Zatorre, Belin & Penhune, 2002). At the peripheral level, there has been evidence to suggest functional biases in the cochlea. There have been various studies suggesting greater TEOAE amplitudes in the right ear versus the left ear (Bilger, Matthies, Hammel & Demorest, 1990; Sininger & Cone-Wesson, 2004). Researchers have suspected asymmetries at the level of the MOC, as the SOC is the first place in the auditory system that processes information from both ears simultaneously. Khalfa, Morlet, Micheyl, Morgon & Collet (1997) revealed a functional asymmetry of the uncrossed MOC system in humans. According to their work, there was a statistically significant asymmetry in MOC activity in right-handed subjects favoring the right ear. This finding was replicated by Philibert, Veuillet, and Collet (1998) who found significantly larger right ear TEOAE suppression effects in the presence of contralateral broadband noise. The researchers surmised that contralateral stimulation was activating the uncrossed MOC neurons, which suggests a right ear advantage.

Research Questions

The action of the MOCR has been well studied, yet its function still remains somewhat nebulous. Research has explored its efficiency with various stimuli such as tones in steady state noise. However, the real word application of a listeners speech-in-noise difficulties as it relates to their MOC function remains a point of contention amongst researchers. This review is intended to systematically summarize published studies to answer the following questions:

1) Does the research indicate that the magnitude of MOC suppression measured via OAEs is related to a normal hearing subject's ability to recognize speech-in-noise?
2) Are MOC effects measured via OAEs lateralized? Is there a right ear advantage as suggested by Khalfa, Morlet, Micheyl, Morgon & Collet (1997)?

Methods

In the exploration of identifying relevant works, an exhaustive search of online research databases including PubMed, Medline Complete, Scopus and Google Scholar were utilized. Peer-reviewed research articles in the disciplines of audiology, neurology, and otolaryngology were examined. The following keywords were used in numerous search combinations:

otoacoustic emissions, OAE, medial olivocochlear, MOC, suppression, speech in noise, speech-in-noise, *corticofugal, and efferent*. An initial search of these keywords yielded 348 results. Duplicate studies presented that were generated across databases were removed. A screening of articles to remove duplicates and non-English works, along with reviewing titles and abstracts reduced the number to 206 results. Also, the reference sections of screened articles were manually reviewed to detect relevant items that did not appear in the direct search. Figure 2 demonstrates the search process of determining articles to be utilized for review.

Inclusion/Exclusion Criteria

Relevant studies published from the year 1997 to 2016 were included. Included studies were from a variety of countries, such as United States, United Kingdom, Germany, India, Turkey and Malaysia.

To reduce the influence of confounding factors, careful consideration was taken into which studies were included for review. Firstly, examining the participants of the studies was of great interest. For the sake of relevancy and direct comparison, only studies testing human subjects were selected for review. Animal studies of any kind were eliminated. Studies that recruited children as subjects were excluded, to remove the influence of research directly related to auditory processing disorders. All subjects were deemed by the researchers as having normal hearing sensitivity and were not older than 65 years of age. The added complication of hearing loss and an aging auditory system would potentially contaminate efferent system measures (Kim, Frisina D., & Frisina R., 2012). Articles were also excluded if the stimulus in noise was not speech.

Studies not written in English, or if they could not be directly translated into English were also eliminated. Furthermore, studies that did not have a full-text version available were discarded. In the present climate of research conducted on this subject, the majority of the studies conducted are quasi-experimental or correlational studies. There are limited, if any, controlled experiments on MOC suppression and speech in noise performance in normal hearing individuals. Thus, in this review, only case studies, expert opinion articles, clinical experience pieces, and consensus conference reports were eliminated, for being lower levels of evidence according to the American Speech-Language-Hearing Association (ASHA) guide of Evidence-Based Practice (2006).

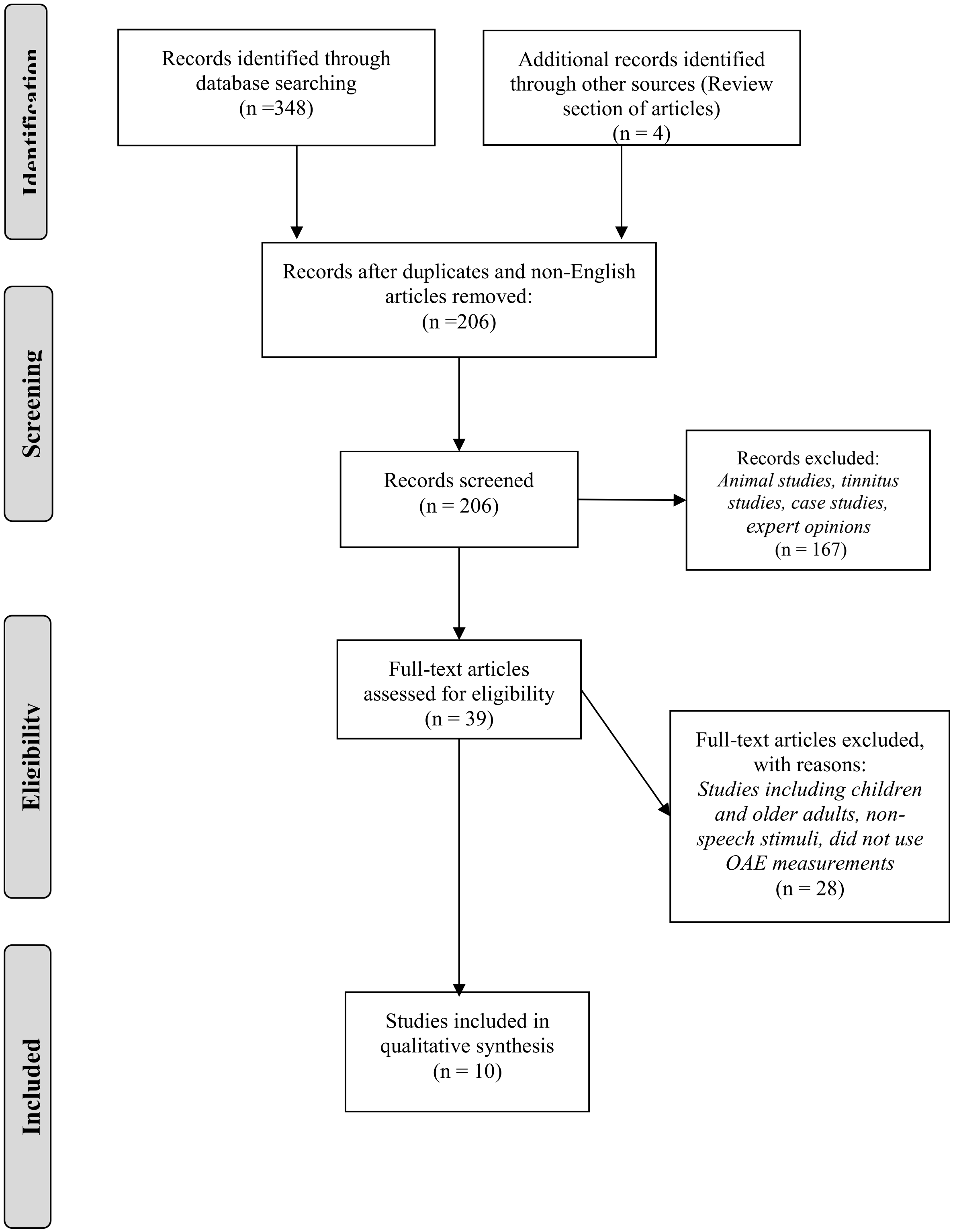

Figure 2: Flowchart of article search and selection process. Adapted from Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009).

Results

Study Characteristics

A summary of the study characteristics of the included ten articles is illustrated in Table 1. The sample size of subjects examined ranged from 13 to 69. All of the subjects were young or mid-age adults, as ages of the participants spanned from 19 to 60 years old. None of the studies included children (individuals under the age of 18) or older adults (individuals over the age of 65). In all ten studies, the hearing and middle ear status of the subject were deemed "normal." Acoustic reflex measurements were either quantified or simply classified as within normal limits in nine of the articles. Though gender has been shown to have effects of OAE measurement (McFadden,2009), seven of the ten studies included subjects of both sexes. In only four experiments did researchers elect to include women subjects only. The overwhelming majority of the articles utilized click-evoked otoacoustic emissions (CEOAE). For this systematic review, the terminology CEOAE will be synonymous with TEOAE since all the researchers specified that the transient evoked stimuli were clicks only. Only two studies selected to use DPOAEs.

Authors	n	Age	Gender	Male	Female	Normal Hearing	ART	Initial OAE SNR	BBN levels	OAE type	Stability	Reproducibility	Time window	Ear Number	Handeness
Bidelman & Bhagat (2015)	15	M=25.5	B	N/A	N/A	≤10 dB 250-8000Hz	measured but not specified	N/A	_	CEOAE	_	_	8-18 ms	Binaural	right handed
de Boer, Thornton, & Krumbholz (2012)	24	M= 22.6	B	12 (50.0%)	12 (50.0%)	<15 dB 500-8000Hz, with the exception of 1 subject with 25 dB at 8000Hz	_	_	40 dB SL	CEOAE	_	≥70%	6-16 ms	Monaural (right only)	right handed
Garinis, Glattke & Cone (2011)	13	20-33/ M= 24.6	W	0 (0.0%)	13 (100%)	dB not specified; HWNL 500-4000Hz	≥60 dB SPL	≥6 dB SPL	60 dB SPL	CEOAE	≥70%	_	6-18 ms	Binaural	right handed
Giraud et al. (1997)	20	M=40.1	B	N/A	N/A	<15 dB 250-8000Hz	_	_	30 dB SL	CEOAE	_	_	2.5-20 ms	Monaural (right only); binaural of	_
Harkrider & Smith (2005)	31	19-40	B	N/A	N/A	<20 dB 250-8000Hz	measured but not specified	_	65 dB SPL (3 subjects required 67–70 dB SPL)	CEOAE	_	>85%	0-20 ms	Monaural (right only)	_
Mishra & Lutman (2014)	18	21-30	B	10 (55.6%)	8 (44.4%)	dB not specified; HWNL 250-8000Hz	>60 dB SPL	≥6 dB SPL	30 dB SL	CEOAE	≥85%	_	_	Monaural (right only)	_
Mukari & Mamat (2008)	40	YA : 20-30/M= 26.3 OA: 50-60/M=55.2	B	16 (40.0%)	24 (60.0%)	<20 dB 250-2000Hz,<25 dB at 4000Hz	_	≥3 dB SPL	30 dB SL	DPOAE	_	_	_	Monaural (chosen at random)	_
Stuart & Butler (2012)	32	M= 22.1	W	0 (0.0%)	32 (100%)	≤20 dB 250-8000Hz	"normal levels", but not specified	≥6 dB SPL	60 dB SPL	CEOAE	≥80%	_	_	Binaural	_
Tokgoz-Yilmaz et al., (2013)	69	18-53/ M= 34.16	B	35 (50.7%)	34 (49.3%)	≤15dB 250-6000Hz	subtraction method	≥3 dB SPL	40 dB SL	CEOAE	≥70%	_	_	Binaural	_
Wagner et al., (2008)	49	19-41/M=25.2	B	19 (38.8%)	30 (61.2%)	dB not specified; HWNL 125-8000Hz	≥80 dB SPL	≥6 dB SPL	60 dB SPL	DPOAE	_	_	_	N/A	_

Table 1: Study Characteristics. Key: “B” = Both genders, “W”= Women only, “OA”= older adults, “YA” = younger adults, “N/A”= not applicable, “-“ = value not specified by researchers, “M”= arithmetic mean

In addressing the second research question, four of the ten articles examined ear laterality. Of these three articles, two carefully selected only right-handed individuals. The remaining did not specify the handedness of the subject. Arguably, the most varied aspect of all of the articles was the assessment of speech in noise intelligibility. Table 2 outlines the levels of speech examined and types of speech testing employed.

Speech Level	Authors	Speech Test	SNR ratio	Outcome Measure
Phoneme	Harkrider and Smith (2005)	NU6 words	0 dB	Phonemes correct (%)
Syllable	de Boer, Thorton and Krumbholz (2011)	*[da] vs.[ga]	10 dB	Consonant vowel discrimination threshold (%)
Words	Garninis et al. (2011)	*Multi-syllable word list presented forwards (active listening) and backwards (passive listening)	-3 dB	Correct classification of words
	Giraud et al. (1997)	Fournier Word List		(%)
	Mishra and Lutman (2014)	Four Alternative Auditory Feature	Various	Speech recognition threshold (in dB)
	Tokgoz-Yilmaz et al. (2013)	*Monosyllabic phonetically balanced word list	10 db	Speech reception in noise scores (%)
Sentences	Bidelman and Bhagat (2015)	QuickSIN	Various	SNR loss (in dB)
	Mukari and Mamat (2008)	HINT	Various	Reception threshold for sentences (in dB)
	Stuart and Butler (2012)	HINT	Various	Reception threshold for sentences (in dB)
	Wagner et al. (2008)	Oldenburg Sentence Test	Various	Speech reception threshold (in dB)

Table 2: Speech Intelligibility tests and Outcome Measures. Key: *= researchers did not specify a name for the speech test, NU6 = Northwestern University Auditory Test Number Six (Tillman, & Carhart, R., 1966), HINT= Hearing in Noise Test (Nilsson, Soli, & Sullivan, 1994), QuickSIN= Quick Speech In Noise Test (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004)

Research Question 1:

Does the research indicate that the magnitude of MOC suppression measured via OAEs corresponds to a normal hearing subject's ability to recognize speech-in-noise?

Researchers correlated measures of MOC activity with contralateral suppression of otoacoustic emissions and speech in noise measures. Speech-in-noise assessments varied by levels of speech and by type of test as previously outlined in Table 2. Despite these differences in outcome measure, ample evidence can be drawn from the studies.

Phonemes and Syllables in Noise

Two of the ten studies chose to evaluate the speech in noise intelligibility at the sub-word level.

At a very basic level of speech, Harkrider and Smith (2005) sought to determine if the subjects' ability to recognize phonemes in noise could be related to measures of efferent auditory activity by way of the subject's CEOAE suppression. Thirty-one normal hearing subjects were asked to repeat 50 monosyllabic words from the NU6 word list at 55 dB HL, with 55 dB of multitalker babble presented in the ipsilateral ear. The subjects' phonemic recognition in noise ability was calculated by the dividing of the total number of phonemes in the NU6 word list and the total number of correct phonemes. In a separate condition, the same subjects' CEOAE responses were collected with and without broadband noise routed to the contralateral ear. These responses were subtracted from each other within an 8 and 18 msec time interval to derive the CEOAE suppression measure. Statistical calculation using Pearson product-moment correlations determined that phoneme recognition in noise did not significantly correlate to the contralateral suppression of CEOAEs. The researchers concluded that the subjects' MOCR activity could not account for the subjects' ability to recognize phonemes in competing noise.

A study by deBoer, Thornton and Krumbholz (2012) looked at CEOAE suppression and speech in noise abilities using consonant-vowel (CV) discrimination task. Twenty-four normal hearing subjects participated in three separate experiments: 1) discrimination of recorded CV syllables, [da] vs. [ga], at 40 dB SL with +10 SNR of broadband Gaussian noise presented to the right ear only, 2) measurement of CEOAE suppression in the right using 60 dB and 70 dB clicks with broadband Gaussian noise presented to the left ear. The input/output (I/O) slope of the OAE amplitude was calculated with and without noise, and an increase in slope represented cochlear gain reduction. The third experiment of recording of auditory brainstem response (ABR) measurements in response to the syllable [da] embedded in +10 dB and +20 dB SNR of broadband Gaussian noise was intended to create a "speech ABR". The researchers indicated that in the presence of noise, speech ABRs have been shown to have latency shifts and amplitude reduction that could possibly predict speech-in-noise performance. The results indicated that there was a significant positive correlation ($r= 0.68$; $p<0.0001$) between I/O suppression and CV in nose thresholds. This finding is opposite of the antimasking hypothesis which would expect better speech in noise performance in the subjects with greater CEOAE suppression. Instead, in the 22 men and women who were included in the final correlation calculation, the greater individual MOC reduction of cochlear gain suggested poorer speech-in-noise discrimination. The ABR results were similar, as the higher the I/O suppression the greater the noise induced latency shift ($r= 0.74$; $p<0.001$). It was expected to have smaller noise induced latency shifts with higher MOC suppression. The researchers noted that statistical analysis indicated that sex-related differences and audiometric thresholds did not play a role in the surprising findings.

Words in Noise

By using speech-in-noise tasks to evaluate word intelligibility in subjects, the following studies scrutinized the connection between MOC effects and speech intelligibility at a higher level of speech.

One of the seminal studies exploring the relationship between MOC effectiveness and speech-in-noise intelligibility was completed by Giraud, Garnier, Micheyl, Lina, Chays & Chéry-Croze (1997). Twenty normal hearing subjects and five vestibular neurotomized (VNT) subjects were utilized to investigate two concepts: 1) To compare speech in noise abilities of subjects with healthy ears and operated ears and 2) To assess the relationships between MOC function via OAE suppression and speech-in-noise performance in both groups. Subjects in the normal hearing group were only examined using their right ear and subjects in the VNT group were subjected to testing in their operated ear and their healthy ear for comparison. First, all subjects were tested with words from the Fournier word list, which comprises of French monosyllabic words. The words were presented at 10 dB above their speech threshold in quiet with -20dB to +20dB SNR of ipsilateral broadband noise. Also, scores were recorded for words and phonemes correctly identified in different ipsilateral noise levels and in the presence and absence of 30 dB SL of contralateral broadband noise. Then, CEOAEs were measured with and without contralateral white noise (bandwidth 0.5-8 kHz) focusing on 2.5-20 millisecond time window to view MOC suppression activity. The results revealed that there was a significant improvement in word recognition scores by about 15 % and 24% with the addition of contralateral broadband noise in the normal hearing subjects ($p<0.05$), and in the healthy ear of the VNT subjects ($p<0.02$) respectively. There was no improvement in the operated ears of the VNT subjects. Two of the five VNT subjects were "disturbed" by the presentation of the contralateral broadband noise. In addition, there was a significant correlation between word recognition score and OAE suppression with contralateral broadband noise in the normal hearing subjects(r=0.56; p<0.01). There was a significant difference in OAE suppression between the healthy ears and VNT ears (p<0.05). The researchers concluded that their questions were answered twofold: 1) There was a significant difference in speech recognition performance in normal hearing subjects compared to the affected ear of VNT subjects in the presence contralateral broadband noise and 2) There was a strong positive correlation with the amount OAE suppression and word recognition score in normal hearing subjects as compared to the VNT subjects. In light of these differences, Giraud et al. (1997) suspected that MOC effects and function were at least partly responsible for speech in noise performance.

Mishra and Lutman (2014) focused on the affiliation between CEOAE suppression and subject's performance on the Four Alternative Auditory Feature (FAAF) test in noise. Eighteen male and female young adults were tasked to identify target words from a choice of four minimally paired words presented at 60 dB SPL in the right ear with ipsilateral noise with varying SNRs. A threshold was obtained at the SNR in which subjects were able correctly to identify the target word 70% of the time. Thresholds were obtained both with and without broadband contralateral noise presented at 30 dB SL. Likewise, two CEOAE measurements were obtained in a separate condition, with and without the same broadband contralateral noise presented at 30 dB SL to view MOC inhibition. The change induced by the contralateral noise was normalized by individual's baseline CEOAE amplitude and compared to their speech-in-noise performance, as measured by their FAAF threshold. The results indicated that the subjects' thresholds were lower with the introduction of contralateral acoustic stimulation, with an average change of threshold of 2.45 dB. The average MOC inhibitory effect was 17.2% when normalized by an individual. The individuals with considerable changes in speech-in-noise performance had more considerable MOC reflexes as measured by their CEOAE suppression and there was a significant correlation(r=0.61, p=0.008). There was no correlation between MOC inhibition and speech in noise performance without contralateral noise. Mishra & Lutman state that while their hypothesis was correct, they acknowledge the relationship between the two variables may not be direct and instead higher auditory centers may be at work along with input from MOC unmasking.

Tokgoz-Yilmaz, Kose, Turkyilmaz, & Atay (2013) approached the examination of contralateral suppression of CEOAE and word in noise performance differently than the abovementioned studies. The researchers assigned 69 normal hearing subjects into two groups. The groups were decided by a seven-question questionnaire created by the researchers to determine perceived speech in noise difficulties. For example, some of the questions were: “Is it difficult for you to understand what is said to you in noisy conditions (e.g. when TV is turned on)?” “Can you carry on a conversation easily in a car or bus?” If a subject indicated at least three “yes” responses, they were placed in the noise complaint group (n=25). The remaining individuals were placed in the no noise complaint group (n=44). Subjects of both groups were evaluated for CEOAE suppression with and without 40 dB SL of contralateral white noise in both ears. Also, the subjects’ speech-in-noise performance was assessed by the percentage of words identified correctly of a monosyllabic phonetically balanced word list presented at 40 dB SL with white noise presented at +10 dB SNR. A Mann-Whitney U test was completed to assess the relationship between speech in noise scores, CEOAE suppression and the presence or absence of speech understanding in noise complaints. Overall, the speech in noise performance was weaker, and the contralateral CEOAE suppression was lower in the noise complaint group. The amount of contralateral suppression at the CEOAE frequency bands of 1-4 kHz was significantly greater in the no complaints group as compared to the noise complaint group, except 4 kHz in the left ear ($p < 0.05$). The researchers concluded the difficulties perceived by individuals with normal hearing sensitivity and speech in noise complaints could be a dysfunction of the MOCR, as compared to their counterparts who do not have difficulty listening to speech in noise.

Sentences in Noise

The remaining researchers sought to evaluate the speech in noise intelligibility at the sentence level.

Mukari and Mamat (2008) sought to determine if MOCR effects measured through DPOAE suppression related to speech perception in noise. The researchers also wanted to compare MOCR function of young adults to older adults. Twenty normal hearing young adults (20-30 years old) and twenty normal hearing older adults (50-60 years old) were assigned to groups that corresponded to their ages. First, DPAOE recordings of all subjects were taken both in quiet and with 30 dB SL of contralateral white noise. The ear of the presentation was randomized. The researchers subtracted the average DPOAE responses with and without noise at each frequency to calculate the amount of suppression. Next, all subjects were tested using HINT sentences under headphones in three conditions: noise presented ipsilaterally to the test ear, noise presented contralaterally to the test ear and noise presented from the front. The amount of noise varied as the test continued to find the SNR at which subjects were able to repeat 50% of the sentences correctly. This value was called the reception threshold for sentences. When statistically analyzed via Pearson correlations there were no significant correlations observed with the speech in noise performance and DPOAE suppression in between group or within group comparison. In general, younger adults had higher DPOAE amplitudes than the younger adults. While younger adults had greater DPOAE suppression as compared to the older adults, this variance in suppression was only significant at 3-8 kHz frequency range. It is also important to note that DPOAE suppression was not found to correlate with pure tone thresholds. The only aspect in which younger adults performed significantly better than older adults, was in the noise-ipsilateral condition ($p<0.01$). The researchers deduced that older adults had a reduced ability to discern speech signals from the background noise when not spatially separated. Mukari and Mamat gathered that the hypothesis of speech perception in noise being related to contralateral DPOAE suppression was not supported since these two measures had no correlation.

Wagner, Frey, Heppelmann, Plontke, & Zenner (2008) also studied the association between speech in noise performance and MOC activity measured by DPOAE suppression. The speech test utilized in this study was the Oldenburg Sentence test, a German sentence task. Forty nine normal hearing subjects of both genders were asked to repeat each sentence at various presentation levels while the noise was held constant at 65 dB SPL in sound field. The level at which the speech was presented adapted based on the subjects performance until the speech reception threshold was obtained at the level at which 50% of the material was understood. The speech testing was repeated over span of three days with different sentence lists to account for a training effect. To evaluate MOC activity the researchers recorded DPOAE suppression in the presence of contralateral noise. The researchers analyzed their DPOAE recordings in two ways. The first (Paradigm A) was to view the growth function of the DPOAE and the second (Paradigm B) was to examine the dip frequencies. The dip frequency measurements were calculated by subtracting the amplitude between the dip frequency and the adjacent higher and lower frequencies in the presence of 60dB SPL contralateral broadband noise. When statistically analyzed there was no correlation with either Paradigm A (r=0.117) and Paradigm B (r=0.257) and the individuals speech-in-noise performance.

<u>Research Question 2:</u>

Are MOC effects measured via OAEs lateralized? Is there a right ear advantage as suggested by Khalfa, Morlet, Micheyl, Morgon & Collet (1997)?

The following studies examined if there would be a difference in the strength of the MOCR between ears.

Garninis et al. (2011) investigated ear differences in OAE suppression levels and speech-in-noise abilities of twenty right handed women with normal hearing. These subjects all had baseline CEOAE responses of 6 dB or greater at four out of five 1/3 octave bands between 1.0-5.0 kHz. All subjects also had contralateral acoustic reflex thresholds above 60 dB SPL to prevent involvement of the middle ear reflex. Subjects were tested in seven total conditions. In the first condition subjects listened to broadband noise with no speech in the contralateral ear. The second condition, deemed the active listening condition, asked subjects to listen to words presented at 57 dB SPL in the presence of 60 dB SPL of background noise (-3 dB SNR). Subjects categorized the presented words in groups by a two-alternative forced choice button press task. Subjects were held to the standard of 85% accuracy to complete the task. In the third condition the same words embedded in broadband noise at the same SNR was backwards. Listeners were not tasked. Researchers called this passive listening. The remaining four conditions were listening to the abovementioned stimuli without noise as a control. The presentation of these conditions were randomized and presented in both ears. Analysis of the CEOAE amplitudes revealed that the greatest amount of suppression occurred in the active listening condition. While right ear CEOAE amplitude was significantly greater than the left ear responses in quiet, there was no significant difference in the amount of suppression exhibited by the right and left ear (2.65 dB right ear vs. 2.57 dB left ear) in the presence of background noise. However, when these results were normalized as compared there was greater left-ear suppression (noise presented to the right and probe measured by the left) – with 44% suppression in the left ear and 38% in the right ear. Researchers concluded this finding is indicative of a right ear advantage.

Bidelman and Bhagat (2015) recruited fifteen normal hearing young adults for their study to investigate the relationship between speech in noise skills ability and MOC activity via contralateral suppression of CEOAEs in both ears. CEOAEs were obtained in each ear with and without the presence of contralateral broadband noise. The level of the contralateral broadband noise was not reported, but the researchers assured the level of the broadband noise failed to reach middle ear reflex thresholds. The amount of suppression was calculated by determining the average difference between CEOAE measurement with and without contralateral noise. Bidelman and Bhagat analyzed CEOAE waveforms from 8ms to 18 ms, and more minutely in 2ms intervals from 2 ms to 20 ms to observe temporal changes. In a separate task, the fifteen subjects' performance was measured using the QuickSIN test. The QuickSIN test is a list of sentences which are embedded in multitalker babble noise. The signal to noise level decreases with each sentence, which allows for the calculation of a subject's signal to noise ratio loss. The QuickSIN sentences were presented at 70 dB SPL for this experiment and each ear was tested independently to determine the subject's speech in noise performance. Using Spearman's rank correlation there was a very weak correlation between QuickSIN performance and CEOAE suppression in the left ear ($r=0.01$, $p=0.96$). However, there was a strong negative correlation between in the right ear ($r = -0.62$, $p = 0.014$). Yet, when the right and left ear correlations were compared directly using Fishers r to z transformation, the right ear did not have a significantly better relationship as suspected ($z = 1.79$, $p = 0.037$). Therefore it could be said that while the right ear does show a stronger relationship between speech in noise ability and CEOAE suppression, it is not significantly better than the left ear. The researchers suggested however, the evidence of a large correlation in the right ear suggests laterality and right ear advantage in MOC activity.

Stuart and Butler (2012) aimed to find the relationship between MOC activity via contralateral suppression of CEOAEs and speech recognition ability in both continuous and interrupted noise. The abovementioned studies all used constant noise in their studies. Stuart and Butler intended to utilize noise that varied in its temporal characteristics for more realistic stimuli. They hypothesized that subjects with better performance in speech recognition tasks would have greater CEOAE suppression values. They also surmised, that the subjects' differences in performance in with the two types of noises (release from masking) should positively correlate with a higher amount of CEOAE suppression. Thirty-two normal hearing females were tested with the Hearing in Noise Test (HINT) presented binaurally and monaurally in both quiet and competing continuous and interrupted broadband noise at 50 dB SL. The intensity level of the sentences varied to calculate the RTS value which was the SNR at which subjects had 50% correct performance. CEOAEs were collected with and without a contralateral white noise suppressor at 65 dB SPL from 2.5– 20 milliseconds. The difference between the CEOAE amplitude with and without noise was deemed to be the amount of suppression. The results revealed that the subjects performed significantly better ($p < 0.001$) in interrupted noise than with continuous noise. There were no predictive linear relations or significant correlations between the magnitude of CEOAE suppression and the subjects' performance of in any of the speech in noise conditions. In regards to laterality, no significant differences could be observed for differences in CEOAE suppression between ears, and there was no correlation between CEOAE suppression and RTS SNR difference scores for the right, left, or binaural conditions. Stuart and Butler acknowledged that the results did not support their hypothesis and stated that CEOAE suppression could not assess an individual's ability to recognize speech in noise as an indicator of MOC strength.

Discussion

The present paper was created to review existing research to reconcile the role of the medial olivocochlear activity in speech-in-noise performance in normal hearing listeners. The following questions were asked: 1) Does the research indicate that the magnitude of MOC suppression measured via OAEs is related to a normal hearing subject’s ability to recognize speech-in-noise? 2) Are MOC effects measured via OAEs lateralized? Is there a right ear advantage as suggested by Khalfa, Morlet, Micheyl, Morgon & Collet (1997)? The compilation and assessment of the ten articles included in this paper do not provide a distinct notion that there is a direct link between MOCR and speech-in-noise capabilities.

In regards to the first research question, seven articles provided insight into if the magnitude of MOC suppression corresponded to the normal hearing subject’s ability to recognize speech-in-noise. Of the seven, Harkrider and Smith (2005), Mukari and Mamat (2008) and Wagner et al. (2008) did not find significant correlations. Out of the remaining four, Giraud et al. (1997), Mishra and Lutman (2014) and Tokgoz-Yilmaz et al. (2013) found significant favorable correlations (better speech recognition performance with increased MOC activity). de Boer, Thorton and Krumbholz (2011) found a significant adverse correlation (worse speech recognition with increased MOC activity). The second research question also garnered mixed results from the four articles, which examined laterality of the MOCR. Bidelman and Bhagat (2015), Garninis et al. (2011) and Tokgoz-Yilmaz et al. (2013) articles found significant laterality – all pointing to a right ear advantage. Stuart and Butler (2012) article found no difference between ears.

Methodical differences

The vast differences of the methodology utilized across the studies likely have an impact on the variability of the findings. A summary of the study characteristics and outcomes can be found in Table 3. As already mentioned and displayed in Table 2, the speech-in-noise material differed in levels of speech. Interestingly enough, all of the studies that examined speech-in-noise performance at the word level found significant correlations for both in regards to MOCR activity and laterality. The transducer and ear used for the presentation of noise differed between articles. For example, Mukari & Mamat (2008) who did not find a significant correlation utilized headphones and noted that with the use of noise in three conditions, there was increased performance when speech and noise were presented contralaterally most likely due to spatial separation. Therefore the speech perception scores could be impacted by the direction of the noise. Also, while there is rationale provided by McFadden et al. (2009), which demonstrates better OAE amplitudes in men compared to women, only a small minority of the studies chose to use women only.

Authors	OAE	Speech Level	Noise Condition	SNR	Transducer	Avg. Suppression	Main findings	Correlat-ion
SIGNIFICANT CORRELATIONS								
de Boer, Thornton, & Krumbholz (2012)	CEOAE	Syllables	Contra	+10 dB	Headphones	-	Significant correlation between CEOAE amplitude reduction and speech in noise measures. However, against researchers	r= 0.68 (p<0.001); r= 0.48 (p=0.028)
Giraud et al. (1997)	CEOAE	Words	Ipsi	-10 dB to +10 dB	Headphones	-	Significant correlation between word recognition and CEOAE amplitude reduction in normal hearing ears. This was not seen in the VNT group	r= 0.56 (p<0.01)
Mishra & Lutman (2014)	CEOAE	Words	Ipsi and Contra	Adaptive	Headphones	1.61 dB	Significant correlation	r=606 (p=0.0008)
Tokgoz-Yilmaz et al., (2013)	CEOAE	Sentences	Ipsi	+10 dB	Headphones	-	Significant positive correlation between speech understanding and amount on suppression. Subjects with no noise complaints had greater suppression amounts.	"significant" at p<0.05
SIGNIFICANT LATERALITY								
Bidelman & Bhagat (2015)	CEOAE	Sentences	-	A	-	-	Right ear advantage	RE: -0.62 (p=0.0014), LE:

								0.01 (p=0.96)
Garinis, Glattke & Cone (2011)	CEOAE	Words	Contra	-3 dB	Inserts	RE=3.14-3.33 dB; LE= 2.7-3.0 dB	Right ear advantage	-
NON-SIGNIFICANT CORRELATIONS								
Harkrider & Smith (2005)	CEOAE	Phonemes	Ipsi	0 dB	Inserts	2.06 dB	Phoneme recognition in noise not significantly correlated to the amount of contralateral CEOAE suppression	-
Mukari & Mamat (2008)	DPOAE	Sentences	Ipsi, Contra and Front	A	Headphones	-0.86 +/- 2.02 dB	No significant correlation between contralateral DOPAE suppression and speech perception in noise	-
Wagner et al., (2008)	DPOAE	Sentences	Front	A	Loudspeaker	0.6-6 dB	No statistical relationship between speech in noise intelligibility and DPOAE suppression	r=0.105
NON SIGNFICIANT LATERALITY								
Stuart & Butler (2012)	CEOAE	Sentences	Ipsi and binaural	A	Inserts	RE= 0.9 dB; LE=1.0 dB	No significant difference between ears.	"no significant difference" at p>0.05

Table 3: Findings. Key: "-": researchers did not specify a value, "A"= Adaptive SNR, "Ipsi"= ipsilateral, "Contra"= Contralateral "RE"= right ear, "LE"=left ear

It is also important to note that while there are systematic differences, there are also commonalities that contribute to the strength of the findings. All of the studies took into account middle ear reflexes when obtaining results. The suppressor noises did not go above 50 dBSL as suggested by Berlin, Hood, Hurley, & Wen (1994), or 65 dB SPL to prevent contraction of the contralateral stapedial muscle. Also, the contralateral suppression levels were all obtained by subtracting individual's differences in OAE amplitudes, regardless of OAE type. More importantly, the definition of suppression was all consistent with the change in amplitudes were compared to the individual's baseline.

Limitations

Within the individual studies, there were some limitations. Some confounding variables, such as memory and cognitive status, were not evaluated. These factors could potentially affect the top-down processing involved in the speech in noise testing that used sentences which would tax the entire auditory processing system. Tests that utilized smaller speech measures would be less susceptible to memory effects and would focus mainly on intelligibility. Also, questionnaires could have been employed to evaluate users' speech in noise problems. Only Tokgoz-Yilmaz et al. (2013) attempted to evaluate the individual's perceived difficulties, instead of solely relying on scoring from the speech-in-noise tests.

Across the studies, there were some challenges to the external validity. All of the ten studies utilized broadband noise during the speech-in-noise testing. While this method allows for more control of the stimuli, speech babble may be a stimulus more indicative of real-world difficulties encountered by individuals. The current research on this subject consists primarily of correlational studies. While this type of research design is essential to initially reveal relationships between speech in noise performance and MOCR activity, it cannot prove direct influences between the two variables. In other words, correlational studies cannot prove causation. Controlled research experiments should be developed to investigate this subject further.

Conclusion

Individuals with normal hearing and speech-in-noise difficulties are somewhat of a conundrum for researchers and audiologists alike. Assessing speech-in-noise difficulties go further than audiometric thresholds, and answers may lie in evaluating higher centers of the auditory pathway. The antimasking function of the medial olivocochlear reflex has been well-documented. Seminal works (Micheyl & Collet,1996; Liberman & Guinan 1998) provide evidence of the involvement of the medial olivocochlear reflex in the detection of tones in noise. Since then, researchers have extended this idea to incorporate more complex stimuli like speech-in-noise. By utilizing the non-invasive method of contralateral otoacoustic emission suppression, a glimpse of medial olivocochlear action can be observed by researchers.

The systematic review of ten studies investigating the relationship of the medial olivocochlear reflex and speech-in-noise performance revealed that the contemporary research on this topic is contentious. There is inconclusive evidence to show a strong correlation between the magnitude of contralateral otoacoustic emission suppression and a normal hearing subject's ability to recognize speech-in-noise. The current research did not clearly show lateralization or a right ear advantage in the action of the medial olivocochlear reflex as proposed in earlier work completed by Khalfa, Morlet, Micheyl, Morgon & Collet (1997) (1997). While the research did not provide clear answers to the research questions proposed in this review, there is enough variability in the findings to produce future experiments. Current research on this topic is shifting towards studying the involvement of the medial olivocochlear complex in regards to learning effects and auditory training (deBoer & Thorton 2008), and more recently, listening effort (Kalaiah et al., 2017).

With the advancement of research, potential causes of speech-in-noise difficulties experienced by normal hearing individuals can be uncovered, and clinical treatments can be developed. As we learn more about the efferent system's role in speech-in-noise abilities, protocols can be created and incorporated into an audiologist's test battery. The current use of otoacoustic emission suppression measurements in research settings may one day spur promising clinical usage. Until then, further research needs to be completed to determine not only the role of the medial olivocochlear reflex but also its effect, if any, on speech-in-noise performance.

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