Université d'Ottawa | University of Ottawa

Updates in Evoked Potentials:

Frequency Following responses: A window to central auditory system.

Amineh Koravand, Ph.D
Associate Professor & Audiologist
Audiology and Speech-Language Pathology Program
University of Ottawa, Canada

Land Acknowledgment

- We pay respect to the Algonquin people, who are the traditional guardians of this land. We acknowledge their longstanding relationship with this territory, which remains unceded. We pay respect to all Indigenous people in this region, from all nations across Canada, who call Ottawa home.

- We acknowledge the traditional knowledge keepers, both young and old.

- And we honour their courageous leaders: past, present, and future

Declaration of interest

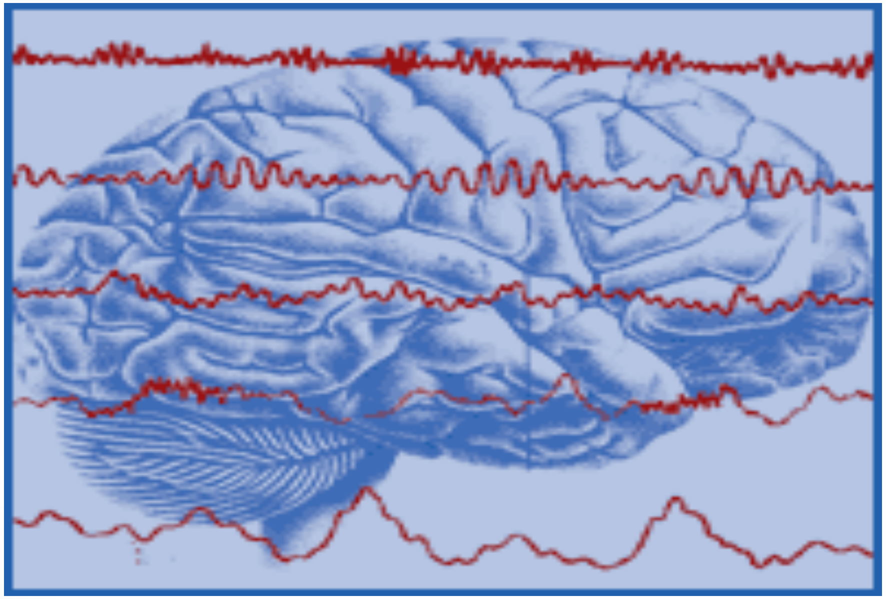
No conflict of interest to declare

uOttawa

Amineh Koravand, Ph.D

Plan of my presentation

- Updated in Evoked Potentials:
  - Clinical versus Research
  - Where are we?
    - New tool?
    - Current literature
    - Brain Lab
      - Barcelona's study



Tirée du http://www.brams.umontreal.ca/cours/files/PSY-6022A2006/DEllemberg

What do we know so far?

Where are we?

“Hearing loss detection”

uOttawa

Amineh Koravand, Ph.D

Introduction:
Hearing loss detection/identification

Universal neonatal hearing screening (UNHS), also known as early hearing detection and intervention program (EHDI):

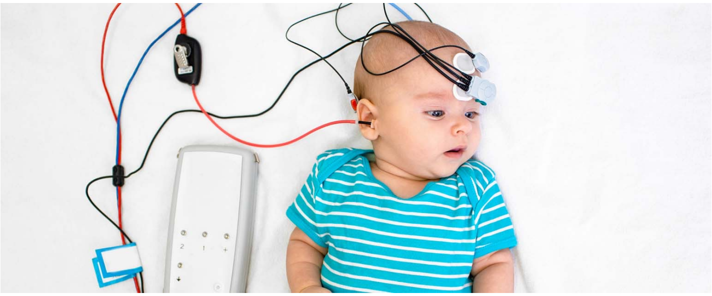
Identification, intervention, and follow-up of newborns with congenital deafness and hearing loss.

Performed worldwide

otoacoustic emissions (OAE)

automated auditory brainstem responses (AABR)

Different protocols based on the risk factors

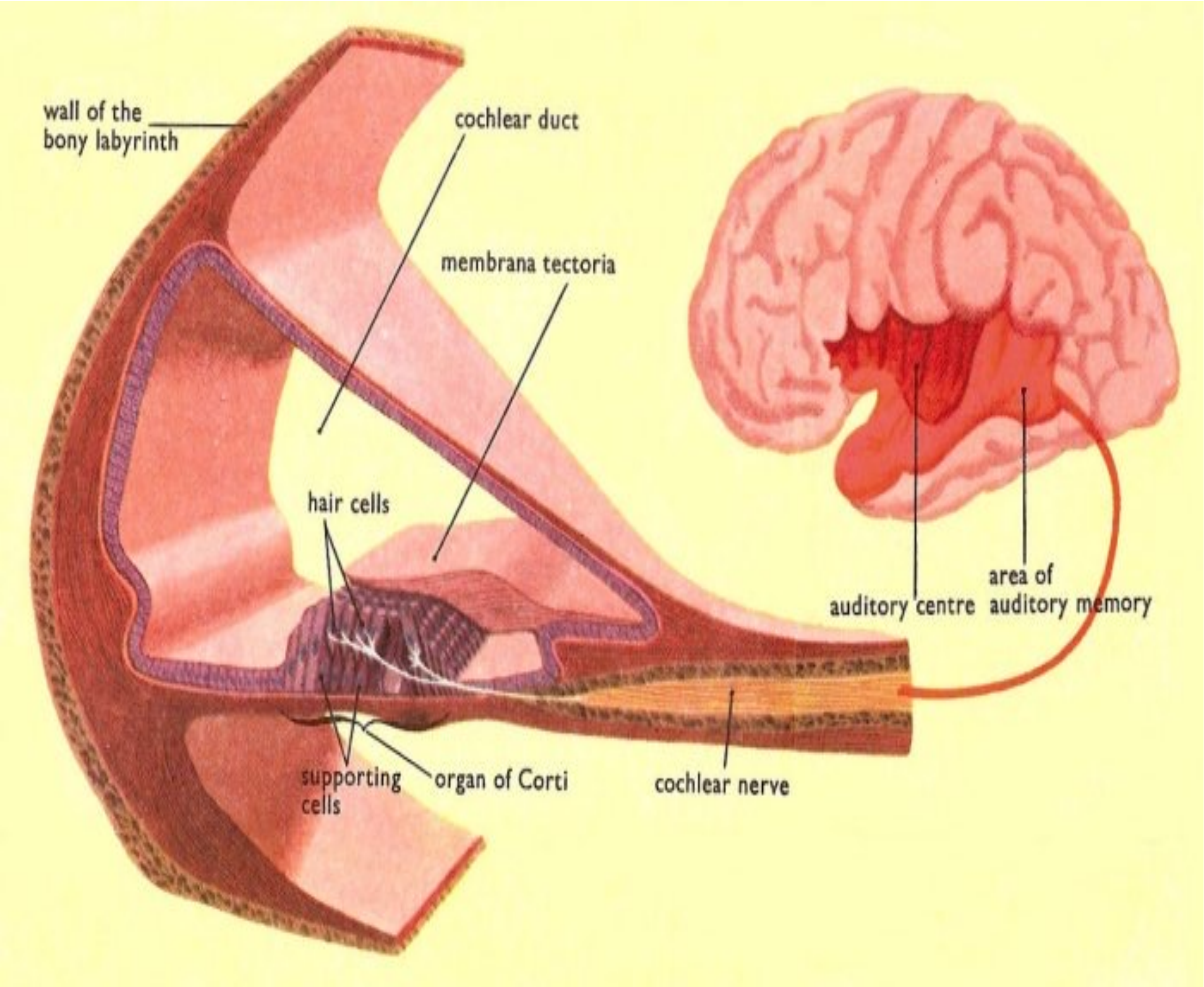


https://www.audiology.org/could-newborn-hearing-screenings-be-used-to-identify-children-with-autism-spectrum-disorder/

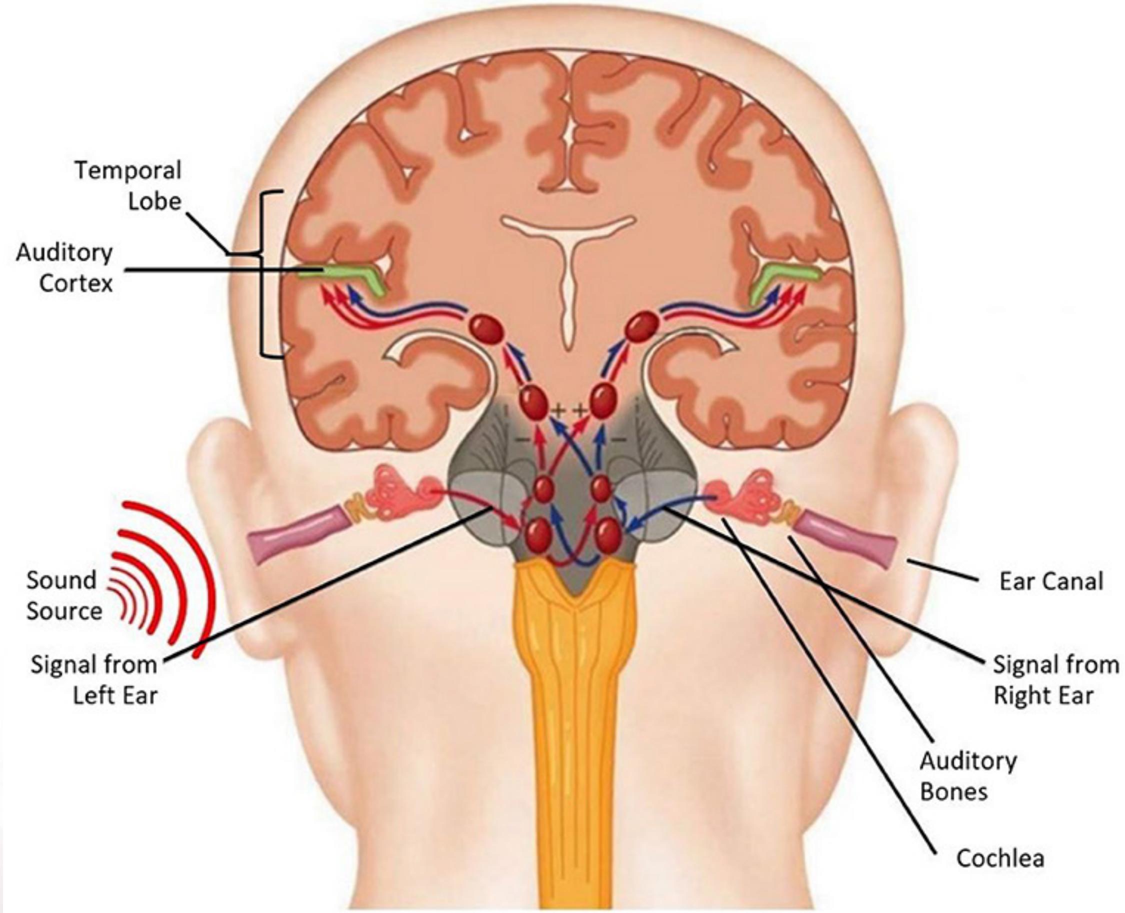
Is it enough?
It depends on……….

uOttawa

Amineh Koravand, Ph.D



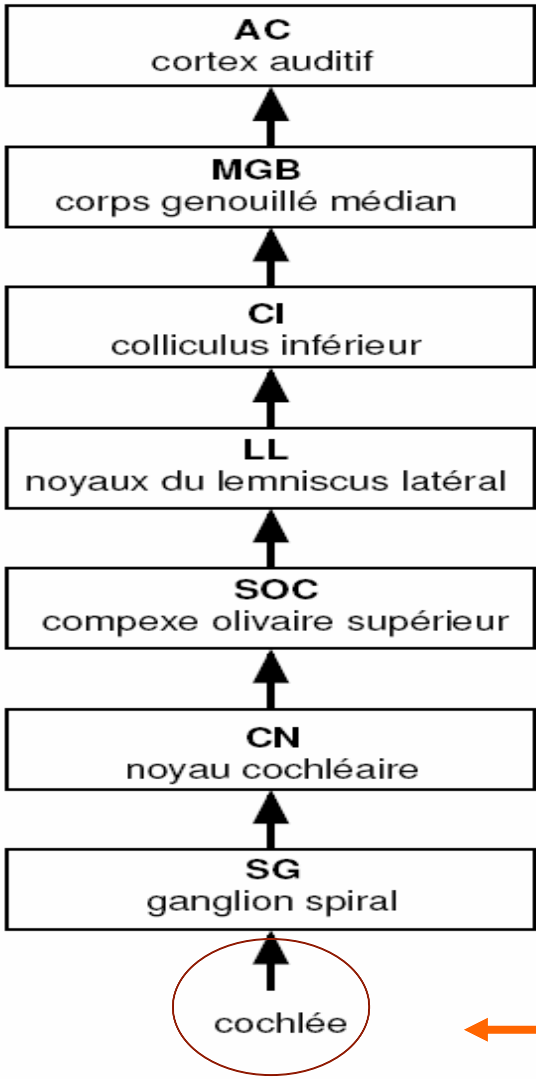
www.daviddarling.info/.../O/organ_of_Corti.html

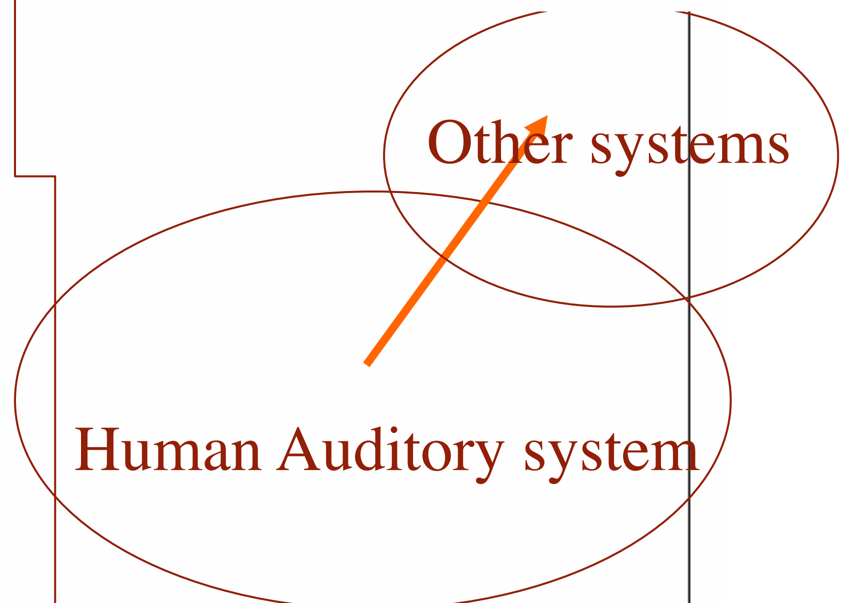


Son → Oreille → Cerveau

(système auditif périphérique)

(système auditif central)





(CISG-SLPA, 2012; Millet et al., 2012)

Hiérarchie ascendante des principaux niveaux du système nerveux auditif.

uOttawa

Is it enough to detect the presence of sound?
It depends on……….

Amineh Koravand, Ph.D

Is it enough?

Children who were born healthy and passed the UNHS could have

- **neurodevelopmental delays/disorders (autism)**
- deficits in language acquisition, reading comprehension, reading acquisition, dyslexia, specific language disorders, auditory processing disorders, etc
- consequent impact on their cognitive function and emotional regulation, and the corresponding socioeconomic negative impact.

Current clinical situation

To date, there is a lack of objective procedures for

early detection of newborns at risk for Listening/language processing difficulties during the first moments of life

The identification of these disorders occurs when

No expected typical behavior ? or

displays an altered or deficient behavioral pattern

Hope / Dream

to detect a potential language/central auditory impairment at birth in a similar manner as congenital deafness

Potential clinical measure/tool ?

Potential clinical measure/tool ?

- Objective, familiar
- Can be recorded with **a similar equipment** used in the AABR test of the UNHS.

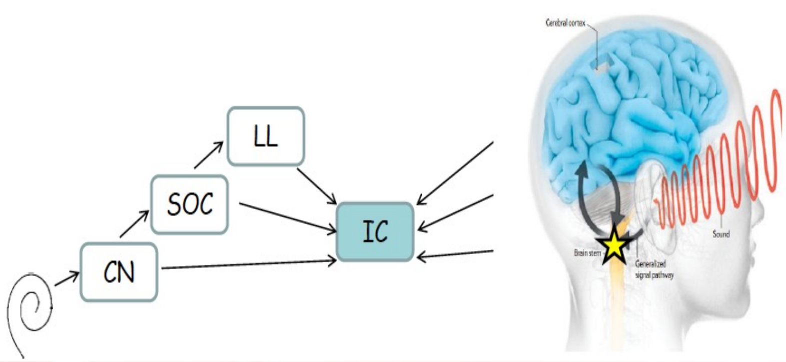
- Continuous efforts to improve the quality of hearing assessments have led to increased interest in new stimuli (the rich acoustic information) and modalities,
  - **such as use of speech in electrophysiological recordings or speech ABRs and, more particularly, the second part of the speech ABR, referred to as the "frequency-following responses" (FFRs to the speech).**

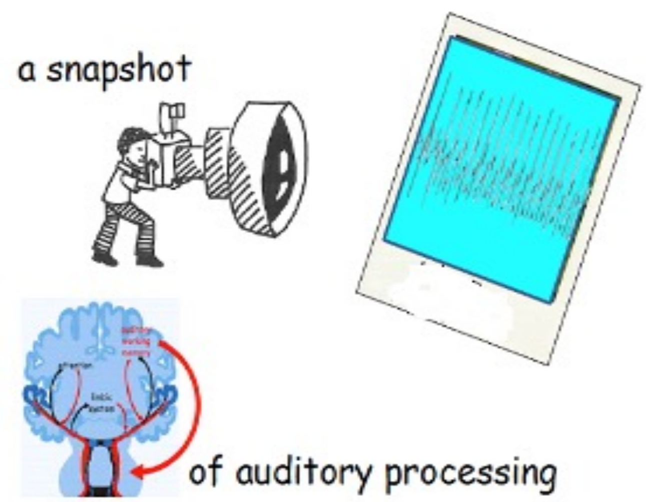
- Produced by the **synchronous activity of neurons of the subcortico-cortical network**

Bidelman, 2018; Chandrasekaran & Kraus, 2010; Coffey et al., 2017, 2019.

Potential clinical measure/tool ?
FFR to speech sound

- The FFR reflects the capacity of encoding **<u>the temporal and spectral features</u>** of speech (Coffey et al., 2019)
  - **Provides a window to explore the integrity of the auditory pathway beyond the mere transmission of sound**





http://www.soc.northwestern.edu/brainvolts/

What is FFR

FFRs can be recorded noninvasively from the scalp with electroencephalography (EEG) and magnetoencephalography, and emerge between 7 and 15 milliseconds from sound onset to auditory frequencies in the range of 100 to 1,500 Hz.

FFR is a sustained and periodic auditory evoked potential that reflects synchronous neural phase locking to the spectrotemporal components of the acoustic signal in the ascending auditory system.

Is it S-ABR, c-ABR, FFR, ASSR, subcortical responses etc?

- This neural response has been termed throughout the literature with other names that have been used interchangeably or which highlight a specific aspect or variant of the response. These include S-ABR, c-ABR, FFR, ASSR, subcortical responses
- The scientific community has agreed that the term "FFR" is the most accurate one, as it refers exclusively to what the component is: a response that follows the frequencies of the incoming stimulus.

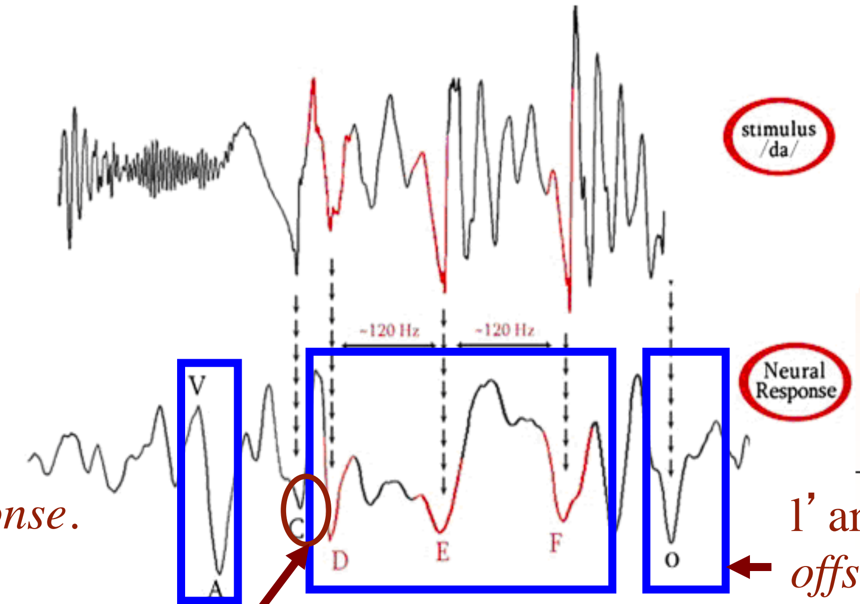
FFR to speech sound

- The FFR has great potential **to answer both basic and applied questions** about the processes involved in sound encoding, language development, and communication.
- It can be obtained through **passive and active listening paradigms** and, by decomposing the recorded signal into **temporal and spectral domains.**
  - (e.g., detection and tracking of the fundamental frequency [F0] and harmonics; e.g., Krishnan, 2002).

- It provides an objective indicator of the fundamental acoustic features intrinsic to speech sounds, including
- **time (onset & latency),**
- **pitch (fundamental frequency, F0), and**
- **timbre (the harmonics)**

Krizman & Kraus, 2019; Skoe & Kraus, 2010

40 ms /da/



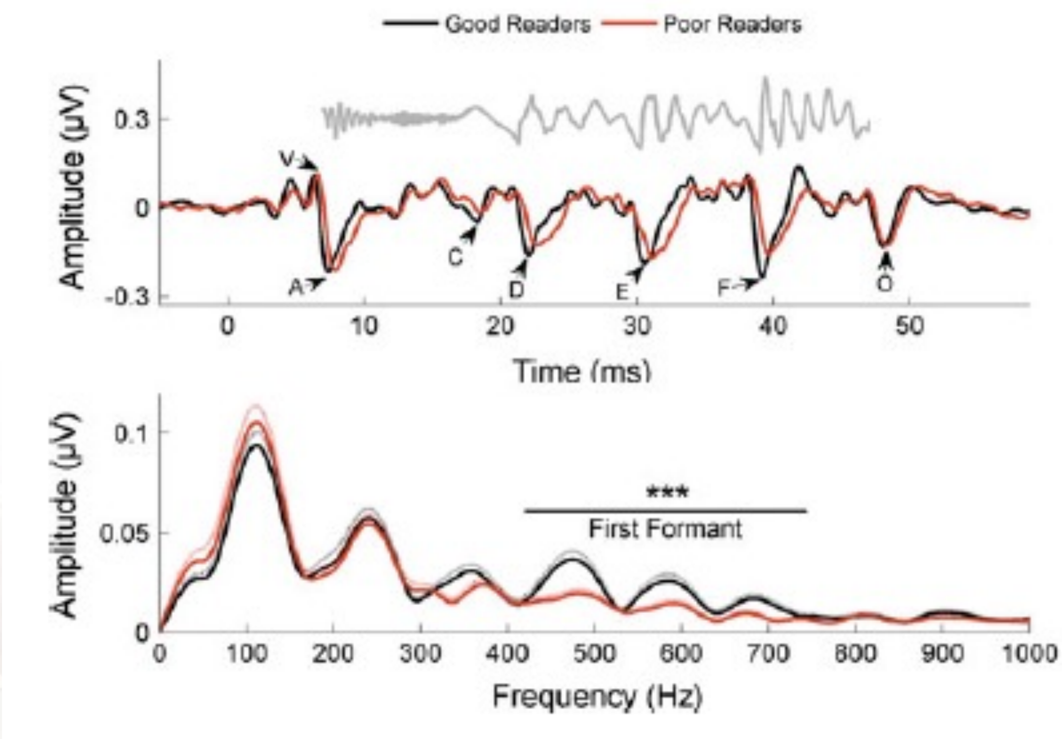
onset-response.

l' arrêt du son
offset.

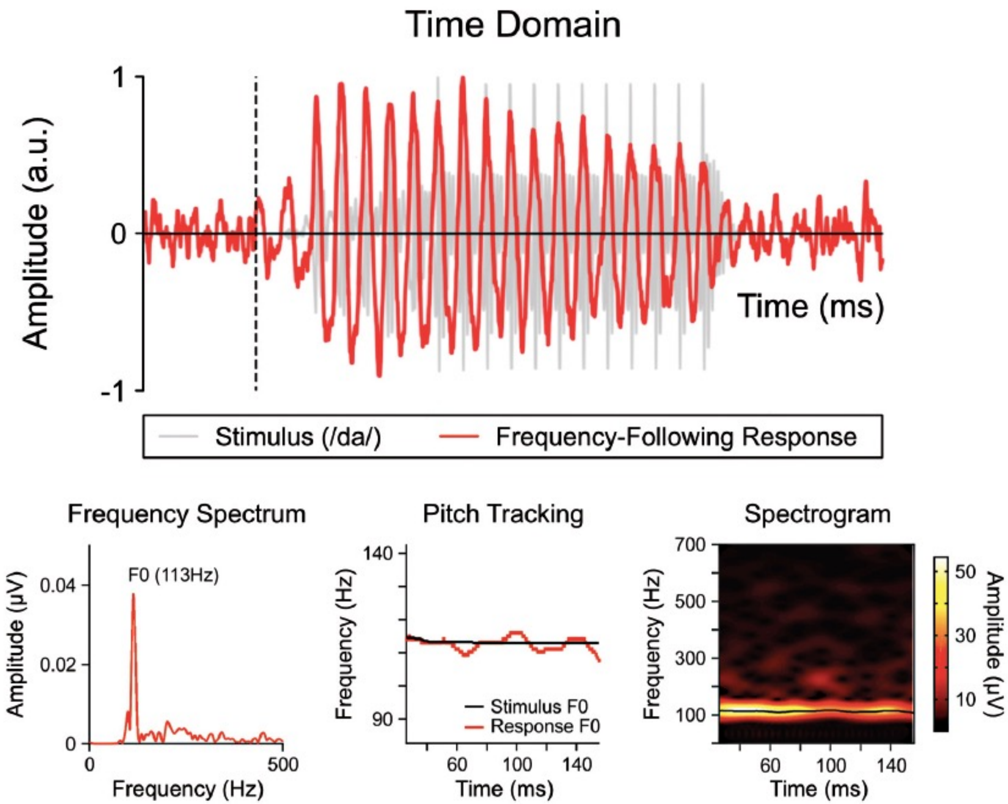
réponse aux harmoniques et à la structure périodique de la voyelle

Kraus N, Nicol T, Zecker S, Skoe E. Auditory Neuroscience Laboratory, Northwestern University

40 ms /da/


Good Readers
Poor Readers
Amplitude (µV)
0.3
0
-0.3
V
A
C
D
E
F
O
0
10
20
30
40
50
Time (ms)
Amplitude (µV)
0.1
0.05
0
***
First Formant
0
100
200
300
400
500
600
700
800
900
1000
Frequency (Hz)

FFR
170 ms /da/



uOttawa

Amineh Koravand, Ph.D

FFR Analysis

FFR allows

- studying the latency and amplitude of the neural response elicited to incoming sounds in the **time domain**.
- analyzing the frequency components of the neural response in the spectral domain, the magnitude with which the fundamental frequency and harmonics have been encoded (Fig 170 ms da).

The analysis

- How **well subcortico-cortical network neurons track temporal** (phase locking) **and frequency** (neural phase locking at the pitch period) characteristics of different stimuli (Krizman & Kraus, 2019; Skoe & Kraus, 2010)
- Provides a window to understand
  - **experience, context, and challenging conditions, such as listening in noise, age, and speech and language disorders.**

Short Video

- https://www.youtube.com/watch?v=qEQuM_rpI6I&t=72s

JSLHR

Review Article

Characteristics of the Frequency-Following Response to Speech in Neonates and Potential Applicability in Clinical Practice: A Systematic Review

Céline Richard,[a,b] Mary Lauren Neel,[a] Arnaud Jeanvoine,[a]
Sharon Mc Connell,[a] Alison Gehred,[c] and Nathalie L. Maitre[a,d]

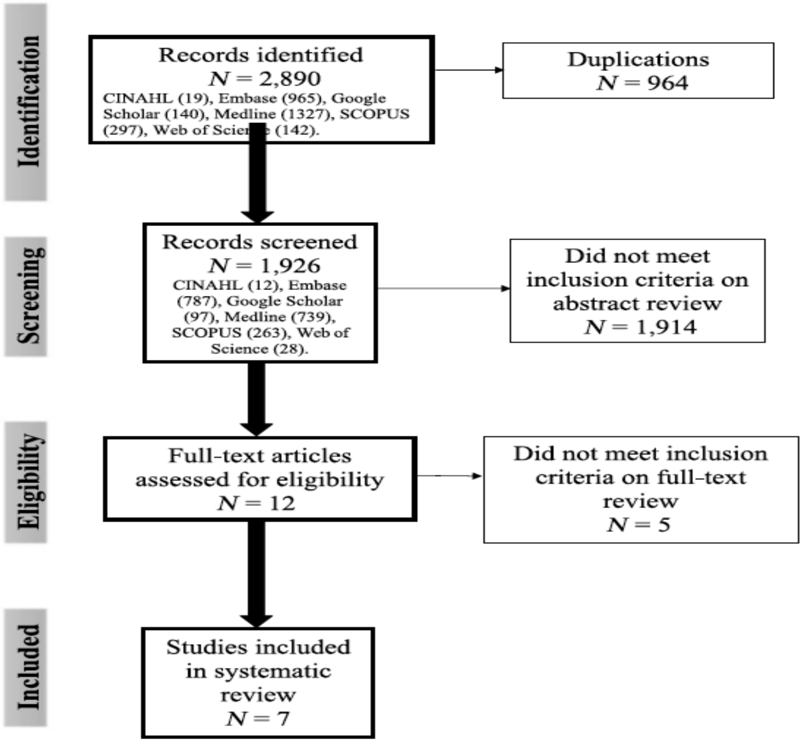
uOttawa

Amineh Koravand, Ph.D

Important clinical questions

1. Can the FFR in response to speech be performed in newborns with an easy, rapid methodology at infant bedside in the nursery?
2. Can stimuli used to elicit the FFR be universally valid, even across cultures and languages?
3. What quantitative information on speech processing will the neonatal FFR provide?
4. Can the FFR in response to speech provide normative data with regard to speech perception and maturation at either cohort or individual levels?
5. Does the FFR have validity in clinical use for diagnosis, early intervention/rehabilitation, and follow-up?

Figure 1. PRISMA-based flowchart of articles selection. CINAHL = Cumulative Index to Nursing and Allied Health Literature.



Important clinical questions

1. Can the FFR in response to speech be performed in newborns with an easy, rapid methodology at infant bedside in the nursery?

   -Yes: with minor modification (ex: More sweeps, REA, binaural is better)

2. Can stimuli used to elicit the FFR be universally valid, even across cultures and languages?

   -Yes: 40 ms and or 170 ms /da/

   - other stimuli as well

Important clinical questions

3. What quantitative information on speech processing will the neonatal FFR provide?

- tracking of voice pitch encoding
- neural phase-locking magnitude
- Other important processing information

Important clinical questions

4. Can the FFR in response to speech provide normative data with regard to speech perception and maturation at either cohort or individual levels?

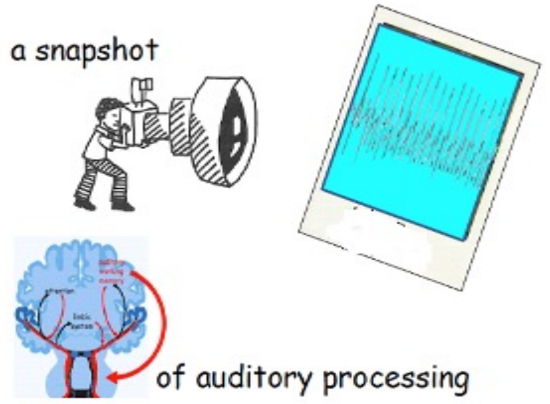
- Normative data regarding neonatal FFR were collected both at the cohort and individual levels.
- Maturational changes within the first 3 months of life.
- **Major limitations**.
  - Cohort size in this review, with four studies having a very limited number of subjects.
  - variability between subjects
  - limited prenatal history

Important clinical questions

5. Does the FFR have validity in clinical use for diagnosis, early intervention/rehabilitation, and follow-up?

Current evidence suggests that the FFR could be **a promising tool in the objective evaluation of speech representation** in the **neonatal subcortico-cortical network.**

It provides **an essential snapshot of neurophysiological markers of speech processing in children.**



http://www.soc.northwestern.edu/brainvolts/

uOttawa

TECHNICAL ASPECTS FOR OBTAINING A NEONATAL FFR: STIMULATION, RECORDING, AND ANALYSIS PROCEDURES

uOttawa

Amineh Koravand, Ph.D

Table 1 Recommended Preparation and Recording Parameters to Record Neonatal and Adult FFRs

Preparation	Recommendation	Rationale
Adults	Recording performed in an electrically and acoustically shielded room	Recording carried away from any type of electrical and acoustical interference
	Participant instructed to relax and not move during the recording. Instructed to blink at a normal pace and eye activity recorded with a vertical and horizontal electrooculogram	Avoid possible muscle movements that could contaminate the recording
	Clean the facial area where electrodes will be placed with (1) alcohol, (2) abrasive gel, and (3) alcohol again	Important to remove sweat, makeup, and other residuals that might be on the skin. The second cleaning with alcohol is important to remove all the rest of abrasive gel and avoid causing irritation when placing an electrode on top of it
	After the recording, remove the electrodes using a gauze or a cotton pad soaked with alcoholic solution or using an adhesive remover such as Niltac	Remove the facial electrodes with minimum harm
Newborns	Recording performed in the hospital room at the maternity ward, with the baby in its crib or in the mother's bed without skin-to-skin contact	Recording carried away from any type of electrical interference, including the electricity from the adult's own skin. If the bed is electrical, it is recommended to be disconnected
	Participant sleeping throughout the whole FFR recording. It is recommended that the recording is performed ~15 minutes after feeding to ensure a deep sleep	Avoid possible muscle movements that could contaminate the recording
	Clean the facial skin area where electrodes will be placed with (1) abrasive gel and (2) alcohol or saline solution	Remove residual substances from birth. Especially important as newborns can still have vernix caseosa on the skin

Article published online: 2022-10-26

Neonatal Frequency-Following Responses: A Methodological Framework for Clinical Applications

Natália Gorina-Careta, Ph.D.,[1,2,3,4] Teresa Ribas-Prats, Ph.D.,[1,2,3] Sonia Arenillas-Alcón, M.Sc.,[1,2,3] Marta Puertollano, M.Sc.,[1,2,3] M. Dolores Gómez-Roig, M.D., Ph.D.,[3,4] and Carles Escera, Ph.D.[1,2,3]

uOttawa

Amineh Koravand, Ph.D

Published in final edited form as:
Ear Hear. 2010 June ; 31(3): 302–324. doi:10.1097/AUD.0b013e3181cdb272.

Auditory brainstem response to complex sounds: a tutorial

Erika Skoe[a,+] and **Nina Kraus**[a,b]

[a] Department of Communication Sciences, Northwestern University

[b] Departments of Neurobiology & Physiology; Otolaryngology; Northwestern University

Published in final edited form as:
Hear Res. 2019 October ; 382: 107779. doi:10.1016/j.heares.2019.107779.

Analyzing the FFR: A tutorial for decoding the richness of auditory function

Jennifer Krizman[1], **Nina Kraus**[1,2,†]

Effects of background noise on the encoding of speech sounds in neonates:
A frequency-following response (FFR) study

Koravand A.,, Alejandro Mondéjar-Segovia, Llobet-Gil, R., Arenillas-Alcón, S., Costa-Faidella, J., Konczol, A., Ribas-Prats, T., Gómez-Roig, C., & Escera, C

Amineh Koravand, Ph.D
Associate Professor & Audiologist
Audiology and Speech-Language Pathology Program
University of Ottawa, Canada

Background

- Infants and young children need **a greater SIN ratio** than adults (Erickson & Newman, 2017; Sobon et al., 2019; Leibold et al. 2019; Leibold et al., 2016).
- **Learning difficulties have also been associated with a stronger vulnerability to noisy environments** (Bradlow et al., 2003).
    - For example, children and young adults with autism spectrum disorder (ASD) (Alcántara et al. 2004), dyslexia (Dole et al., 2012) or specific language impairment (Ziegler et al., 2005; Ziegler et al., 2011) **have significantly poorer speech perception in noise** compared to typically developing children.
- This difficulty can be exacerbated by developmental deficits during the first years of life and can eventually lead to language difficulties.

Background

- Studies focusing on the neurophysiological basis of SIN processing have suggested that the worsening influence of noise in speech processing **may result from the interference of speech encoding at the brainstem level** (Anderson & Kraus, 2010; Song et al., 2011; White-Schwoch et al., 2015).

- Speech-in-noise FFR responses have been studied in adults and in children with normal and/or abnormal SIN processing (Anderson & Kraus, 2010; Song et al., 2011; White-Schwoch et al., 2015, Presacco et al. 2016, Koravand et al, 2019)

Important elements

- FFR reflects the encoding of temporal and spectral features of speech sounds and is disrupted in a wide range of language-related disorders.

- The effect of background noise on speech processing during the earliest stage of life has not been investigated using FFR.

Amineh Koravand, Ph.D

Objectives

to explore the possibility of using FFR as a potential biomarker for measuring speech in noise (SIN) in babies.

More specifically: to document the feasibility of recording FFRs in babble noise in neonates within a maternity ward during the days immediately after birth and to compare this effect against that from a reference group of adults.

Hypothesis

Based on recent finding regarding early speech in quiet perception in newborns (Ribas et al., 2019) and SIN perception in infants (Musacchia et al, 2018), we hypothesized

1. Newborns would obtain consistent **FFRs to speech in quiet and in a noise**.
2. A **greater background noise effect on F0 encoding in newborns** than in adults. This effect would be expressed strongly during the consonant transition region

Method

- **Participants:**
  - 25 healthy term newborns (14 females; aged 30.67 ± 2.85 hours after birth) recruited from the Sant Joan de Déu Children's Hospital in Barcelona (Catalonia, Spain)
    - Exclusion criteria : Apgar score, passing UNHS, no complication during the birth
  - 25 adults (15 females, aged 27.32 ± 1.08 years) were recruited from the University of Barcelona.
    - No history of psychiatric or neurological disorder, nor hearing impairments

Method

- Preceding FFR recording
  - wave V. ABR was obtained by using a standard click of 100 μs square-wave click presented at 65 dB sound pressure level (SPL) in both age groups.
- FFRs were recorded to **/da/ syllables in quiet and in ipsilateral babble noise** for the latter (S/N= +10), respectively.
  - /da/ syllable with a duration of 170 ms and a fundamental frequency (F0) of 113 Hz
  - **The /da/ syllable is divided into three segments:**
    - an onset period of 10 ms,
    - 47 ms consonant transition (10-57 ms)
    - 113 ms of steady vowel section (57-170 ms).

Method

- The noise condition was assessed by playing **a Spanish six-talker babble noise (4 females and 2 males, 75 s track) at 55 dB SPL** (at 10 dB attenuated intensity
- **Rate of 3.7 Hz** with an inter-stimulus interval of 100.27 ms.
- **Alternating polarities** to the **right ear** through ER3C Etymotic shielded earphones of 300 Ω (ER, Elk Grove Village, IL, EEUU) connected to a Flexicoupler adaptor (Natus Medical Incorporated, San Carlos, CA) in newborns, and to a custom-made earcup in adults.

Method

Data acquisition

- Stimuli were delivered using a SmartEP platform including the cABR and Advanced Hearing Research modules (Intelligent Hearing Systems, Miami, Fl, EEUU).
- **Six blocks of 1000 /da/** repetitions were presented in two different conditions (**three blocks per condition**): quiet and noise.
- The noise condition consisted on the simultaneous presentation of the /da/ stimulus and the babble stimulus.
- Auditory conditions were alternated to reduce possible neural adaptation.

Data acquisition

Babies Data Acquisition

- Neonatal FFRs were recorded while neonates were sleeping in their bassinets at their hospital rooms.
- Recording was paused at any sign of wakefulness or movement, cancelling it if sleep could not be restored.

Babies Data Acquisition

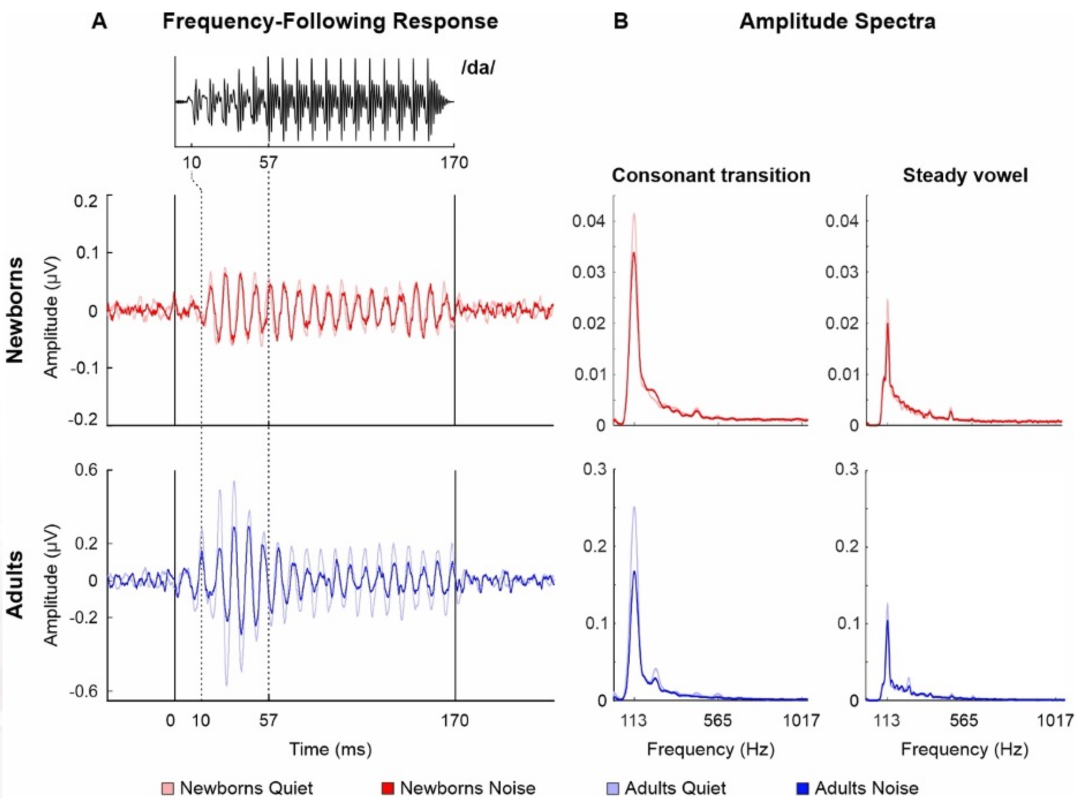
- Total duration of the recording was approximately **38.80 (± 1.14) minutes**
  - (two click blocks×2000 sweeps×51.81 ms SOA, plus six /da/ blocks×1000 sweeps×270 ms SOA, plus the duration of rejected sweeps).
  - Additional 5 minutes were spent in the preparation time, including electrode positioning, checking for impedances and electrode removal.
  - The average time also included the time necessary to recover sleep in cases where the recording session was interrupted by demonstrated discomfort or sleep disturbance in the newborns.

Method: Data pre-processing and analyses

- The continuous EEG signal was acquired at a sampling rate of 13333 Hz, applying an online bandpass filter from 30 to 1500 Hz and dividing it into epochs of 270.27 ms (including 40 ms of pre-stimulus baseline).

- Three FFR parameters were retrieved from the recordings in time and frequency domains for both sections of the stimulus **(Consonant transition and steady vowel)** separately.
  - Root mean square [RMS] of the prestimulus region,
  - Signal-to-noise ratio [SNR] of the brain response,
  - Spectral amplitude.

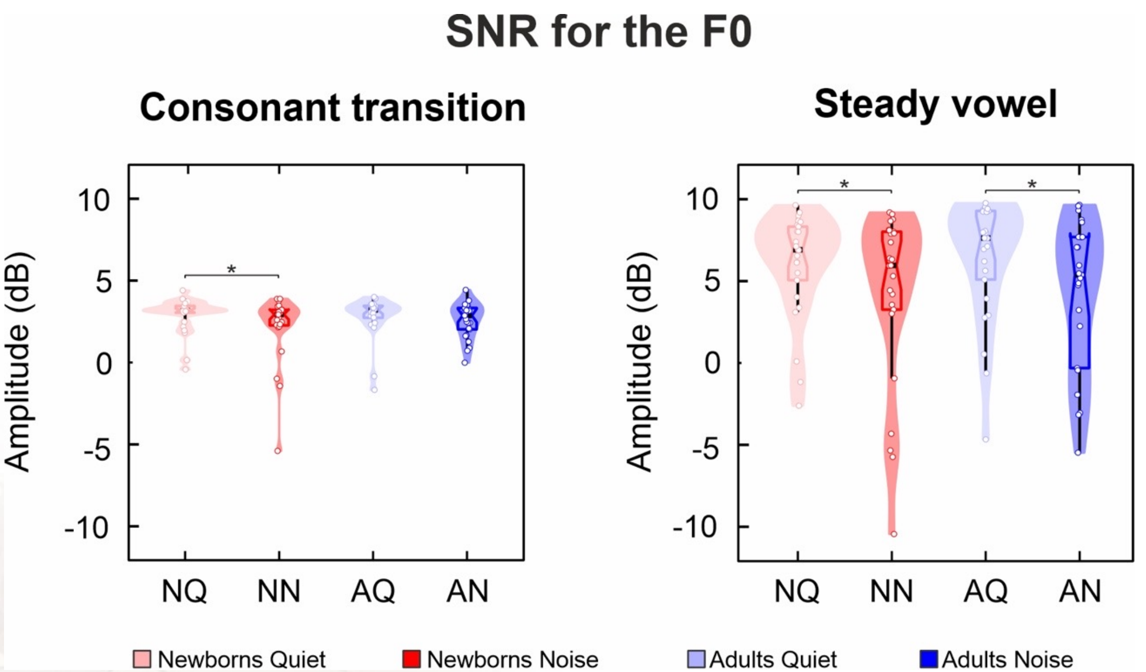
Results



uOttawa

Amineh Koravand, Ph.D

Results



SNR for the F0
Consonant transition
Steady vowel
Amplitude (dB)
10
5
0
-5
-10
NQ
NN
AQ
AN
*
Newborns Quiet
Newborns Noise
Adults Quiet
Adults Noise

Results

Newborns obtained reliable FFRs to speech in quiet and in background noise;

Both newborns and adults exhibited larger signal amplitude to the speech stimulus in silence than when presented in noise

Newborns obtained overall lower values than adults in all parameters except the vowel SNR of the response;

FFR was affected by noise during the consonant transition in two groups.

Newborns experimented the effect of noise in the steady vowel section as well.

Discussion

- Findings suggest that newborns process speech presented in background noise at birth differently, possibly due to their immature auditory system which is exposed to attenuated sounds during gestation.
- This study constitutes the first step towards understanding the development of speech-in-noise (SIN) processing from the first days of life.
- An early detection of FFR abnormalities in processing SIN could lead to earlier intervention of central auditory processing disorders and language difficulties.

Limit of the study

1. Different state of alertness, when sleeping newborns are compared with awake, relaxed adults with their eyes closed, may be a factor contributing to the observed group differences.
   a. attentional modulations of the cortical generators of the FFR (Coffey et al., 2019, 2016; Hartmann and Weisz, 2019)
   b. the extent to which subcortical sources of the FFR are modulated by attention is not well stablished (Hartmann and Weisz, 2019).

Limit of the study

- The presentation intensity
  - Adults versus babies

CONCLUSION

SIN processing can be studied at birth.

Newborns can perceive speech syllables in quiet and noisy environments.

Newborns present impoverished neural encoding of speech in background noise conditions from the very first moment from birth.

Even though, the pattern of disruptions in the neural encoding of speech was different from the adult one, the sensitivity to noise was similar.

Conclusion

This study aims to promote the need for future longitudinal research using FFR in early developmental stages to assess SIN encoding, pursuing to elucidate whether it could become **a predictive biomarker of future auditory processing deficits** and, consequently, **certain language-related disorders**.

Acknowledgements

The authors would like to thank all adults and newborns that kindly participated in the study. This work was supported by the Spanish Science and University Ministry PGC2018-094765-B-I00 project and the MDM-2017-0729-18-2 Maria de Maeztu Center of Excellence (MINECO-FEDER), the 2017SGR-974 Excellence Research Group of the Generalitat de Catalunya, a donations from the Fundación Pedro Salesa Cabo (Barcelona), and the ICREA Acadèmia Distinguished Professorship awarded to Carles Escera.

Bibliography

Alcántara, J. I., Weisblatt, E. J., Moore, B. C., & Bolton, P. F. (2004). Speech-in-noise perception in high-functioning individuals with autism or Asperger's syndrome. *Journal of Child Psychology and Psychiatry, 45*(6), 1107-1114. doi: 10.1111/j.1469-7610.2004.t01-1-00303.x

Anderson, S., & Kraus, N. (2010). Sensory-cognitive interaction in the neural encoding of speech in noise: a review. *Journal of the American Academy of Audiology, 21*(9), 575-585. doi: 10.3766/jaaa.21.9.3

Bradlow, A. R., Kraus, N., & Hayes, E. (2003). Speaking clearly for children with learning disabilities. *Journal of Speech, Language, and Hearing Research, 46*(1),80-97. doi: 10.1044/1092-4388(2003/007)

Coffey, E. B., Nicol, T., White-Schwoch, T., Chandrasekaran, B., Krizman, J., Skoe, E., Zatorre, R. J., & Kraus, N. (2019). Evolving perspectives on the sources of the frequency-following response. *Nature communications, 10*(1), 1-10. doi: 10.1038/s41467-019-13003-w

Dole, M., Hoen, M., & Meunier, F. (2012). Speech-in-noise perception deficit in adults with dyslexia: Effects of background type and listening configuration. *Neuropsychologia, 50*(7), 1543-1552. doi: 10.1016/j.neuropsychologia.2012.03.007

Erickson, L. C., & Newman, R. S. (2017). Influences of background noise on infants and children. *Current Directions in Psychological Science, 26*(5), 451-457. doi: 10.1177/0963721417709087

Kuhl, P. K. (2010). Brain mechanisms in early language acquisition. *Neuron, 67*(5), 713-727. doi: 10.1016/j.neuron.2010.08.038

Kuhl, P. K., Williams, K. A., Lacerda, F., Stevens, K. N., & Lindblom, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science, 255*(5044), 606-608. doi: 10.1126/science.1736364

Leibold, L. J., & Buss, E. (2019). Masked speech recognition in school-age children. *Frontiers in psychology, 10*, 1981. doi:10.3389/fpsyg.2019.01981

Leibold, L. J., Yarnell Bonino, A., & Buss, E. (2016). Masked speech perception thresholds in infants, children, and adults. *Ear and hearing, 37*(3), 345–353. doi:10.1097/AUD.0000000000000270

Musacchia, G., Ortiz-Mantilla, S., Roesler, C. P., Rajendran, S., Morgan-Byrne, J., & Benasich, A. A. (2018). Effects of noise and age on the infant brainstem response to speech. *Clinical Neurophysiology, 129*(12), 2623-2634. doi:10.1016/j.clinph.2018.08.005

Newman, R. S. (2009). Infants' listening in multitalker environments: Effect of the number of background talkers. *Attention, Perception, & Psychophysics, 71*(4), 822-836. doi: 10.3758/APP.71.4.822

Polka, L., Rvachew, S., & Molnar, M. (2008). Speech perception by 6-to 8-month-olds in the presence of distracting sounds. *Infancy, 13*(5), 421-439. doi: 0.1080/15250000802329297

Popelka, G. R., Moore, B. C. J., Popper, A. N., & Fay, R. R. (2016). *Hearing Aids*. New York: Springer Science+Business Media. doi: 0.1121/1.4977603

Ribas-Prats, T., Almeida, L., Costa-Faidella, J., Plana, M., Corral, M. J., Gómez-Roig, M. D., & Escera, C. (2019). The frequency-following response (FFR) to speech stimuli: a normative dataset in healthy newborns. *Hearing research, 371*, 28-39. doi: 10.1016/j.heares.2018.11.001

Richard C, Neel ML, Jeanvoine A, Connell SM, Gehred A, Maitre NL. Characteristics of the frequency-following response to speech in neonates and potential applicability in clinical practice: a systematic review. J Speech Lang Hear Res 2020;63

Schoof, T., & Rosen, S. (2014). The role of auditory and cognitive factors in understanding speech in noise by normal-hearing older listeners. *Frontiers in aging neuroscience, 6*, 307. doi: 10.3389/fnagi.2014.00307

Sobon, K. A., Taleb, N. M., Buss, E., Grose, J. H., & Calandruccio, L. (2019). Psychometric function slope for speech-in-noise and speech-in-speech: Effects of development and aging. *The Journal of the Acoustical Society of America, 145*(4), EL284-EL290. doi: 10.1121/1.5097377

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2011). Perception of speech in noise: neural correlates. *Journal of cognitive neuroscience, 23*(9), 2268-2279. doi: 10.1162/jocn.2010.21556

White-Schwoch, T., Woodruff Carr, K., Thompson, E. C., Anderson, S., Nicol, T., Bradlow, A. R., Zecker, S.G., & Kraus, N. (2015). Auditory processing in noise: A preschool biomarker for literacy. *PLoS biology, 13*(7), e1002196. doi: 10.1371/journal.pbio.1002196

Ziegler, J. C., Pech-Georgel, C., George, F., Alario, F. X., & Lorenzi, C. (2005). Deficits in speech perception predict language learning impairment. *Proceedings of the National Academy of Sciences, 102*(39), 14110-14115. doi: 10.1073/pnas.0504446102

Ziegler, J. C., Pech-Georgel, C., George, F., & Lorenzi, C. (2011). Noise on, voicing off: Speech perception deficits in children with specific language impairment. *Journal of experimental child psychology, 110*(3), 362-372. doi: 10.1016/j.jecp.2011.05.001

Many thanks

Merci beaucoup

Questions?