Otology & Neurotology
40:e1–e6 © 2018, Otology & Neurotology, Inc.

Naunton's Masking Dilemma Revisited

*Sheran Seneviratne, †‡Celene McNeill, §Simon L. Greenberg, and ||Jonathan Kong

**Department of Ear, Nose and Throat Surgery, St George Hospital, Kogarah; †Department of Otolaryngology Head and Neck Surgery, Royal Prince Alfred Hospital; ‡Hearing and Balance Centre, St. Vincent's Hospital Sydney, Sydney; §University of Sydney; and ||Macquarie University, Australia*

Background: Pure-tone audiometry is essential in diagnosing clinical hearing loss. Masking of the nontest ear is mandatory for determining accurate hearing thresholds in the presence of asymmetrical levels between the two ears and for ascertaining the presence of a conductive hearing loss. Paradoxically, over masking occurs when the intensity of the required masking noise to the contralateral ear is such that it exceeds interaural cranial attenuation by an amount sufficient to mask the test ear. Ralph F Naunton was the first to describe this phenomenon, which has since been known as ''Naunton's masking dilemma.''

Methods: A formula was derived mathematically to predict when Naunton's masking dilemma might occur in air and bone conduction. Review of Ralph F Naunton's primary works and related publications was performed.

Results: Our derived mathematical formulae predict when ''Naunton's masking dilemma'' may occur. During air conduction testing, a masking dilemma may occur when the sum of the air/bone gaps is greater than or equal to twice the interaural attenuation minus 15 dB ($\Sigma\ ABG_{NTE+TE} \geq 2 \times IA - 15$ dB). During bone conduction testing, a masking dilemma may occur when the air-bone gap of the nontest ear is greater than or equal to the interaural attenuation minus 15 dB ($ABG_{NTE} \geq IA_{AIR} - 15$ dB).

Conclusion: Naunton's masking dilemma imposes a significant limitation to conventional audiometric testing. To the best of our knowledge, we think this is the first time that Naunton's masking dilemma has been represented in a simplified mathematical equation.

Key Words: Masking—Masking dilemma—Naunton masking dilemma—Pure-tone audiometry.

Otol Neurotol **40:**e1–e6, 2019.

Pure-tone audiometry (PTA) is essential in diagnosing clinical hearing loss. Masking of the nontest ear is mandatory for determining accurate hearing thresholds in the presence of asymmetrical levels between the two ears and for ascertaining the presence of a conductive hearing loss. Theoretically, masking is required to prevent the test signal from crossing over to the nontest ear when it reaches intensity levels above physiological interaural attenuation. Masking using the plateau technique is the most commonly described method within the literature (1–3).

Paradoxically, ''over masking'' may occur when the intensity levels of the masking noise reach limits above physiological interaural attenuation. This occurs when the masking level is so intense that there is a crossover to the test ear, effectively providing masking to the test ear (3). Ralph F Naunton was the first to describe this phenomenon, which has since been known as ''Naunton's masking dilemma'' (4,5). In this article we propose a mathematical formula to help identify scenarios in which ''Naunton's masking dilemma'' may occur.

METHODS

A comprehensive literature review of Dr. Ralph F Naunton's publications between 1952 and 1970 with reference to the presence of a masking dilemma when performing PTA was performed. The accuracy and validity of these descriptions were analyzed by an audiologist and two otologists. A further historical review of Naunton's professional efforts and achievements in advancing research and public health in the field of audiology was also undertaken.

RESULTS AND DISCUSSION

Dr. Ralph F Naunton

Dr. Ralph F Naunton was the first to describe the phenomenon of the masking dilemma, which subsequently became known as ''Naunton's masking dilemma.'' Naunton had an illustrious surgical career pioneering advances in otology on both research and clinical fronts (4).

Born in London, Naunton received his graduate medical training at the University of London. He completed

---

Address correspondence and reprint requests to Sheran Seneviratne, M.B.B.S., M.S., Ear Nose and Throat Surgery, St George Hospital, Kogarah, NSW 2217, Australia; E-mail: sheran.seneviratne1@gmail.com
ORCID No: 0000-0002-4898-7452.

Institution where work was performed: St George Hospital, Kogarah, Sydney, NSW, Australia.

The authors disclose no conflicts of interest.

DOI: 10.1097/MAO.0000000000002043

both audiology and otolaryngology training. In 1954, Naunton left England to do his fellowship with Dr. John Lindsay at the Department of Otolaryngology (University of Chicago, United States of America). He later became Chief of ENT for the department when Dr. Lindsay stepped down in 1966. Naunton served as Chief from 1966 to 1978. He was certified by the American Board of Otolaryngology in 1965 and the American Speech and Hearing Association in 1969. In 1979 he left the University of Chicago as Professor Emeritus of Surgery (Otolaryngology) to join the National Institute of Health, in the United Kingdom (6).

Naunton worked at the National Institute of Health for 16 years, with the National Institute of Neurological and Communicative Disorders and Stroke, where he also supported research to improve the clinical utility of the cochlear implant. As he predicted, the cochlear implant remains the most successful neural prosthesis available. He was also a pioneer in promoting the early detection of hearing loss in infants and furthering research to prevent noise-induced hearing loss.

Naunton received international recognition throughout his career for his contributions to the science of ‘‘hearing and balance.’’ He was a member of the advisory board of many professional associations including the: Deafness Research Foundation; American Otological Society; Better Hearing Institute; and International Hearing Foundation. He was also a member of the International Collegium Otorhinolaryngological Amicitiae Sacrum, as well as various other professional organizations. Naunton passed away in 2004 (7).

Naunton’s Masking Dilemma

Masking is a noise presented to the nontest ear to ensure that the tone presented to the test ear is not heard on the opposite side (1).

Naunton’s masking dilemma occurs when the intensity of the required masking noise is such that it exceeds interaural cranial attenuation and crosses over to the test ear. This causes the adverse phenomenon of over masking, i.e., the masking noise is heard by the tested ear making it impossible to clinically establish the true threshold of the test ear.

Naunton’s masking dilemma accounts for one reason many patients with bilateral conductive hearing losses may have inconclusive audiometric test results. Inconclusive or inaccurate audiometric results have the potential to compromise clinical decision making. Both the air conduction and the bone conduction levels of an ear may be open to question because of this problem (4–10). It is not uncommon for it to occur in cases of otosclerosis and other bilateral conductive hearing loss conditions.

It occurs because sound attenuation across the head is inadequate to prevent unwanted masking of the test cochlea, as an adequate masking volume is required to overcome the air-bone gap of the nontest ear. Every time the masking is increased, the signal tone cannot be heard in the test ear (effectively the test ear is masked out by the crossover sound from the opposite ear). Subsequently the test tone is increased. It needs increasing, until it is heard again, but then the masking noise will cover it, again. Therefore, it is not possible to establish a masking plateau. The use of insert earphones increases interaural attenuation, reducing the likelihood of a masking dilemma. Insert headphones provide increased interaural attenuation due to less surface area being exposed to conduct the sound. Mean interaural attenuation values for different audiometric frequencies for insert and supra-aural headphones have been reported elsewhere and vary substantially (5,9).

Masking

PTA consists of measuring a patient’s hearing thresholds using pure tones at different frequencies via air and bone conduction. The mathematical difference between air and bone conduction thresholds, also known as the air-bone gap, defines whether a hearing loss is of conductive or sensorineural nature. Conductive hearing losses are those that arise by pathology in the external and/or middle ear and are characterized by the presence of an air-bone gap on audiology. Sensorineural hearing losses are those that arise by pathology within the inner ear (cochlear or retro-cochlear) and are characterized by the absence of an air-bone gap (unless a mixed loss is present). Mixed hearing losses arise by a combination of pathology in the external/middle ear (conductive damage) and inner ear (sensorineural damage) (3,5).

During PTA, ‘‘masking’’ is applied to the nontest ear via air conduction using a narrow band noise to mask the specific tested sound frequency, which could be potentially heard by the nontest ear. Masking is required to establish hearing thresholds via air conduction when the difference between the 2 ears at any given frequency is greater than 40 dB or via bone conduction when the difference between air and bone thresholds in the same ear is greater than 10 dB. The transducer used for testing air conduction (supra-aural headphones or in-the ear phones) influences intra-aural attenuation. It is accepted that supra-aural headphones provide attenuation of 40 dB and insert earphones attenuate 50 dB. However, these values vary depending on the specific frequency (11,12,13).

The most accepted masking technique, known as ‘‘The Plateau method,’’ was first described by Hood over five decades ago (12). It has evolved over time until there are multiple reiterations of the technique. In this paper we are referring to the classical method. This method involves a gradual increase in masking to find a plateau in which the threshold of the test ear does not increase. When sufficient masking is presented, there are two to three successive levels of masking that result in no change in threshold in the test ear. Most audiologists consider three consecutive masked levels with a consistent presentation level in the test ear, to be the threshold.

The classical method uses an initial masking noise of 10 dB Sensation Level for the air conduction threshold of the nontest ear. This is followed by increases of 10 dB to

$$\mathbf{MEM\ (A)} = \overbrace{AC_{TE} - IA}^{\text{Amount of sound crossing over to NTE}} + \overset{\substack{\text{Masking needs to overcome presence of}\\ \text{conductive HL of the NTE}\\ \downarrow}}{ABG_{NTE}} + \overset{\substack{\text{Buffer}\\ \downarrow}}{10dB} \qquad (1)$$

$$\mathbf{XUM\ (A)} = \mathbf{IA} + \mathbf{BC_{TE}} - \mathbf{5dB} \qquad (2)$$

FIG. 1. AC testing. The masking levels at which the predicted minimum effective masking and maximum usable masking occur during air conduction testing can be calculated using equations first derived by Liden et al. (1959). NB: ■ MEM = the minimum masking level that makes the test tone of the threshold of the test ear inaudible to the nontest ear. ■ XUM = the highest level of masking that does not cross over and elevate the threshold of the test ear. ■ ABGNTE = masking needs to overcome the presence of a conductive hearing loss of the NTE. ■ IA = interaural attenuation for air conduction. ○ Insert headphones = 50 dB. ○ Supraaural headphones = 40 dB. ■ Buffer = 10 dB. A safety factor to account for test and subject variability + ensure masker actually masks the NTE (3,14).

confirm air conduction thresholds (12). When the masking level is increased three times (30 dB), with no change in threshold, then the threshold measured in the plateau is the actual threshold of the test ear. In the plateau phase, the tone is audible in the test ear and inaudible in the nontest ear due to the masker, whilst at the same time the masker is not sufficiently intense to crossover and elevate the threshold of the test ear. In cases of a significant bilateral conductive hearing loss, the plateau technique breaks down due to cross over of the masking signal and ''Naunton's masking dilemma'' occurs (11,12,14).

Clinical Example: Bilateral Conductive Hearing Loss (>55 dB)

Assuming interaural attenuation using supra-aural headphones is 40 dB, in the presence of a true bilateral

$$\text{MEM (A)} \geq \text{XUM(A)} \qquad (1)$$

$$AC_{TE} - IA + ABG_{NTE} + 10dB \geq IA + BC_{TE} - 5dB \qquad (2)$$

$$AC_{TE} + ABG_{NTE} \geq BC_{TE} + 2xIA - 15dB \qquad (3)$$

$$AC_{TE} - BC_{TE} + ABG_{NTE} \geq 2 \text{ x } IA - 15dB \qquad (4)$$

$$\sum ABG_{NTE+TE} \geq 2 \times IA - 15dB \qquad (5)$$

FIG. 2. Naunton's masking dilemma in AC testing. (1) Naunton's masking dilemma occurs when MEM (i.e., the minimum masking level that makes the test tone of the threshold of the test ear inaudible to the nontest ear) is greater than or equal to the XUM (the level of masking before it crosses over and elevates the threshold of the test ear). As the masking level is increased, the threshold tone remains audible in the TE until the masker crosses over to the TE at a sufficient level to mask the response of the TE. As the masking level continues to increase, the masking threshold of the TE continues to increase. In this region, known as "over-masking," the tone is not audible in the NTE but is audible in the TE at an elevated level above the actual threshold (3,14–16). (2) Previously derived equations expanded out. (3, 4) Algebraic simplification. (5) Since ACTE − BCTE = ABGTE, Naunton's masking dilemma occurs when the sum of the air-bone gaps is greater than or equal to twice the interaural attenuation − 15 dB.

conductive hearing loss of 55 dB threshold via air conduction at a given frequency, the test stimulus will ‘‘crossover’’ and stimulate the nontest ear at a level of 15 dB. Masking is therefore necessary to exclude the nontest ear from the test. Any masking stimulus entering the nontest ear will crossover losing 40 dB en route. However, if the test ear is to remain unaffected, the masking stimulus needs to be 0 dB when it reaches the test ear. A 40 dB mask stimulus loses 40 dB en route and arrives at the test ear at 0 dB. The limit of the masking stimulus entering the nontest ear is therefore 40 dB above threshold and may cause over masking to occur. This clinical case of bilateral otosclerosis is a typical example of the Naunton’s masking dilemma, whereby a masking stimulus fed to the nontest ear effectively masks the test ear (3,15).

FORMULAE

The authors have determined a mathematical equation each for air-conduction and bone conduction testing during PTA that predicts when ‘‘Naunton’s masking dilemma’’ may occur.

Abbreviations:

- ABG = air-bone gap
- AC = air conduction threshold
- BC = bone conduction threshold
- TE = test ear
- NTE = nontest ear
- IA = interaural attenuation (air)
- MEM (A) = minimum effective masking (air conduction)
- MEM (B) = minimum effective masking (bone conduction)
- XUM (A) = maximum usable masking (air conduction)
- XUM (B) = maximum usable masking (bone conduction) (3)

Air Conduction Testing

- Known formula masking (refer to Fig. 1)
- Our proposed formula identifying Naunton’s Masking Dilemma (refer to Fig. 2)

Bone Conduction Testing

- Known formula masking (refer to Fig. 3)
- Our proposed formula identifying Naunton’s Masking Dilemma (refer to Fig. 4)

Occlusion Effect

When masking during bone conduction testing, an ‘‘occlusion effect’’ occurs. When a tone is applied to the test ear, if the contralateral ear is occluded (by either supra-aural or insert headphones), sound leakage from the ear canal is reduced. This results in more sound being able to reach the cochlea of the nontest ear. The occlusion effect applies to differing degrees when either supra-aural (refer to Table 1) or insert headphones are used in the nontest ear (refer to Table 2). The ‘‘occlusion effect’’ occurs primarily in the low frequencies of bone conduction testing (11,12,18).

The result of the occlusion effect is that sound applied to the test ear is more easily heard by the nontest ear, meaning that masking needs to be increased to account for this. At this stage we have not accounted for the occlusion effect in our formula, but this may be considered in future publications (18).

CONCLUSION

Naunton’s masking dilemma imposes a significant limitation to conventional audiometric testing. This

Masking needs to overcome presence of conductive HL of the NTE

$$\mathbf{MEM\ (B)} = BC_{TE} + ABG_{NTE} + 10dB \tag{8}$$

Buffers

$$XUM\ (B) = BC_{TE} + IA_{AIR} - 5dB \tag{9}$$

FIG. 3. BC testing. The masking levels at which the minimum effective masking and maximum usable masking occur during bone conduction testing can be calculated using equations first derived by Liden et al. (1959). The original equations of Liden et al. ignored the occlusion effect. Audiologists readily adjust for occlusion effect in the clinical setting when assessing low frequencies (14–16). ■ MEM (B) = minimum effective masking (bone conduction). ■ XUM (B) = maximum usable masking (bone conduction). NB: ■ ABGNTE = masking needs to overcome the presence of a conductive block of the NTE. ■ IA = interaural attenuation in this formula refers to air conduction (i.e., 40 dB/50 dB). Note masking is applied through air conduction so the amount of masking that crosses over to the TE is influenced by the air interaural attenuation rather than bone interaural attenuation. ■ Buffer = 10 dB. A safety factor to account for test and subject variability + ensure masker actually masks the NTE.

$$MEM(B) \geq XUM(B) \tag{10}$$

$$BC_{TE} + ABG_{NTE} + 10dB \geq BC_{TE} + IA_{AIR} - 5dB \tag{11}$$

$$ABG_{NTE} + 10dB \geq IA_{AIR} - 5dB \tag{12}$$

$$ABG_{NTE} \geq IA_{AIR} - 15dB \tag{13}$$

FIG. 4. Naunton's masking dilemma in BC testing. (10) Naunton's masking dilemma occurs when MEM(B) $\geq$ XUM(B). (17) Previously derived equations as first described by Liden et al. (1959). ■ MEM(B) = represents the amount of masking that must be applied to the nontest ear. When bone conduction is applied to the TE, that same amount of sound will crossover to the NTE (BCTE), hence the amount of masking that must be applied is represented by the bone conduction of the TE plus the air-bone gap of the NTE (as the masking is given by air conduction it needs to overcome the air-bone gape of the NTE) plus a further 10 dB of masking as a buffer to ensure adequate masking. ■ XUM(B) = represents the maximum masking that can be applied before the masking is heard in the test ear. When masking exceeds the bone conduction in the TE plus the interaural attenuation it begins to be heard in the NTE. A −5 dB buffer is further included to ensure adequate masking. (11,12) Algebraic simplification.

dilemma may occur when testing air conduction or bone conduction and can result in inconclusive test results whereby the patient's audiometric thresholds cannot be determined or the validity of the results is uncertain.

During air conduction testing, a masking dilemma may occur when the sum of the air/bone gaps is greater than or equal to twice the interaural attenuation minus 15 dB ($\Sigma\ ABG_{NTE+TE} \geq 2 \times IA - 15$ dB). During bone conduction testing, a masking dilemma may occur when the air-bone gap of the nontest ear is greater than or equal to the interaural attenuation minus 15 dB ($ABG_{NTE} \geq IA_{AIR} - 15$ dB). These two simplified mathematical equations may prove useful clinically as a quick guide to the clinician of when to be careful of a possible masking dilemma arising. Formulas for effective masking, undermasking and overmasking have been derived and are present in the scientific literature. To the best of our knowledge, we think this is the first time that Naunton's masking dilemma has been represented in a simplified mathematical formula.

TABLE 1. *Recommended occlusion effect values for supra-aural headphones*

Frequency (Hz)	250	500	1000	>1000
Occlusion effect (dB)	20	10	5	0

AUDism et al. reported the following values for the occlusion effect (OE) (18).

TABLE 2. *Recommended occlusion effect values for insert headphones*

Frequency (Hz)	250	500	1000	>1000
Occlusion effect (dB)	30	20	10	0

REFERENCES

1. Liden G, Nilsson G, Anderson H. Masking in clinical audiometry. *Acta Otolaryngol* 1959;50:25–136.
2. Martin F. Minimum effective masking levels in threshold audiometry. *J Speech Hear Dis* 1974;39:280–5.
3. Turner R. Making redux II: A recommended masking protocol. *J Am Acad Audiol* 2004;15:29–46.
4. Naunton R. A masking dilemma in bilateral conduction deafness. *Arch otol* 1960;72:753–7.
5. Lenhardt M, Goldstein B, Shulman A. Binaural hearing, atresia, and the masking dilemma. *Int Tinnitus J* 2006;12:96–100.
6. NIDCD's Naunton Is Mourned. 2004, National Institute of Health, Orbituaries. Available at: https://nihrecord.nih.gov/newsletters/03_30_2004/obits.htm. Accessed Nov 5, 2017.
7. 78th Collegium Forum. 2004, Collegium ORLAS. Available at: https://www.corlas.org/wp-content/pdf/annual_report2004.pdf. Accessed Nov 6, 2017.
8. Chaplin RG, Miyamoto RT. The masking dilemma and its solution. Fusion at the inferred threshold (FIT) and sensorineural acuity level (SAL) tests. *Am J Otol* 1983;5:34–9.
9. Studebaker J. On masking in bone conduction testing. *J Speech Hear Res* 1962;5:215–27.
10. Denes P, Naunton RF. Masking in pure-tone audiometry. *Proc R Soc Med* 1952;45:790–4.
11. Fee WE. Clinical application of non-acoustic middle ear muscle stimulation. *Arch Otolaryngol* 1981;107:224–6.
12. Hood J. The principles and practices of bone conduction audiometry. *Laryngoscope* 1960;70:1211–28.
13. Sklare DA, Denenberg JL. Interaural attenuation for tubephone insert earphones. *Ear Hear* 1987;8:298–300.

14. Turner RG. Masking Redux I: an optimized masking method. *J Am Acad Audiol* 2003;15:17–28.
15. Feldman AS. Maximum air-conduction hearing loss. *J Speech Hear Res* 1963;6:157–63.
16. Martin FN. Minimum effective masking levels in threshold audiometry. *J Speech Hear Disord* 1974;39:280–5.
17. Wegel RL, Lane CE. Auditory masking of one pure tone by another and its probable relation to dynamics of the inner ear. *Phys Rev* 1924;23:266–85.
18. Formula masking for pure tone bone conduction testing. Audstudent. 2016. Available at: http://www.audsim.com/mbook/c9.html. Accessed Feb 2018.