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REVIEW ARTICLE **Open Access**

Auditory working memory measures in children with hearing impairment: a systematic review

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Abstract

Auditory working memory (AWM) is the process by which information is held in the brain for a brief duration of time until either it is employed to complete a task, deleted after a short period, or transferred to long-term memory. AWM deficits have been noticed even in children with milder hearing impairments. It is essential to incorporate AWM assessment as a part of the standard audiological battery to minimize the detrimental effects of working memory deficits. The present study systematically reviews the articles published between 2011–2021 regarding test tools available to assess AWM in children with hearing impairment and the efficiency of the same. An overview of the auditory working measures such as the forward and backward digit span test; digit span subtests of Wechsler Intelligence Scale for Children-III; non-word repetition; Illinois test of Psycholinguistic Skills-Forward Digit Span; Numbers reversed subtest from Woodcock-Johnson III Tests of Cognitive Abilities; and Word and non-word recall subtests of Working Memory Test Battery-Children; Number recall, and Word order task from Kaufman Assessment Battery for Children II are provided in detail. The present systematic review also provides an overview of the efficiency of the assessment tools by discussing the correlation between the findings obtained in memory tasks with other auditory, verbal, and visual measures. The working memory performance in children with hearing impairment using a hearing aid or cochlear implant has been found to be affected but varies in nature depending on the degree of hearing loss.

Keywords Auditory working memory, Children, Cochlear implant, Hearing aids

Background

Auditory working memory (AWM) is a process in which an auditory stimulus will be stored in the brain for a brief duration in the absence of the stimulus and used to execute tasks [14]. Encoding-information processing and loading them into the memory storage,maintenance-the active rehearsal and retention of this knowledge for use in the future; and retrieval-the recall or use of the information that was stored, are the three phases of working memory [11].

WM is required for various cognitive functions, including learning, reading, and comprehension [2]. It is also thought to be a good predictor of successful communication and success in school [5]. Normal hearing (NH) children and children with hearing impairment (HI) exhibit variances in the domain of auditory experience in terms of quality and the quantity of the acoustic information affected in children with hearing impairment. This difference might impact the cognitive and linguistic development of HI children [16]. Studies state that the neural networks involved in specific aspects of cognition are affected due to auditory deprivation caused by hearing loss that remains untreated [14, 21]. Since the resources needed for higher-level understanding, such

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as the ability to retain auditory information in memory, must be employed for effectively decoding and interpreting the speech signal, even mild hearing loss may result in decreased performance in related cognitive activities [6, 7, 9]. Also, any changes to WM could propagate to the information processing system and can impact learning and reading as well as other cognitive activities and the distribution of attentional resources [8].

AWM abilities are often overlooked, undermining audiological assessment's efficacy in individuals with hearing impairment (HI). Various tests developed in the recent past to assess this ability have to be included in the test battery to prevent long-term deficits. The current study aims to review the significant studies conducted on tests to assess AWM abilities in children with HI.

Methods

The systemic review was conducted based on the Preferred Reporting Items for Systematic Review and Meta-analyses statement (PRISMA Statement) [13]. A systematic literature search was carried out for peer-reviewed articles published from 2011 to 2021.

Information sources

PubMed/Medline, Google Scholar, and Science Direct were extensively searched for studies on AWM measures in children with HI. Lists of references and citations were searched manually for further relevant studies.

Search strategy

The search was carried out using key terms, related search phrases, derivatives, and MeSH words relevant to the study combined with Boolean operators.

"Working memory" OR "Auditory working memory" OR "Verbal working memory" AND "Assessment" OR "Measures" OR "Recall tests" OR "Digit Span Test" OR "Word Repetition test" OR "Non-word repetition test" OR "Test battery" AND "Children" NOT Auditory Processing Disorders NOT Co-morbid conditions NOT "Adults" were used as the key terms for searching studies.

Study selection

The specific inclusion criteria and exclusion criteria for the selection of studies were as follows:

Inclusion criteria

Original articles with human participants, appropriate samples (minimum sample size of 6 was considered), assessment approaches, and statistics; articles focusing majorly on the assessment of auditory WM (Working Memory); articles focusing on individuals with HI with or without hearing aid/cochlear implants were included.

Exclusion criteria

Articles published in languages other than English with poor methodology; articles on evaluation of those with auditory processing disorders or those with additional co-morbid problems; Editorials, letters to the editor, and case reports were all excluded.

Data extraction

The Rayyan QCRI (Qatar Computing Research Institute) and Mendeley desktop reference manager systems were used to integrate the search results, and the duplicate studies were removed. The studies that met the inclusion criteria were identified by screening the titles and abstracts retrieved from the search strategies. Later, the full text of the potential studies was retrieved and matched to see the eligibility. The extracted data included the article title, author details with their affiliation, year of publication, research design, study population, sample size, age group, comparison group, method of outcome measures, and keywords specific to assessing WM in children.

Quality assessment

The Critical Appraisal Skills Programme 2018 [4] was utilized to evaluate the listed papers' methodological quality.

Results

A total of 17,600 articles were identified using database searches, with 14 duplicates eliminated. 17,586 articles were included in the title/ abstract screening. Following the title and abstract review, 27 articles were selected for the full-length article screening. Ten articles matched the inclusion criteria in the study. The remaining 17 articles were excluded mainly because of the study design and irrelevant study population. A detailed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart for the selection of the study is shown in Fig. 1.

Study characteristics

The study population included children with HI with or without hearing aids and CI (Cochlear Implants). 8/10 studies included participants using CI, while the remaining 2 studies included children using hearing aids. Participants with co-morbid conditions and poor performance in IQ tests were excluded from all the studies. The selected articles assessed AWM abilities directly or using verbal WM in audition mode. Wechsler Intelligence Scale for Children-III in 2 studies, Forward Digit Span and Backward Digit Span in 4 studies, ITPA-FDS in 1 study, non-word repetition in 2 studies, Woodcock-Johnson III Tests of Cognitive

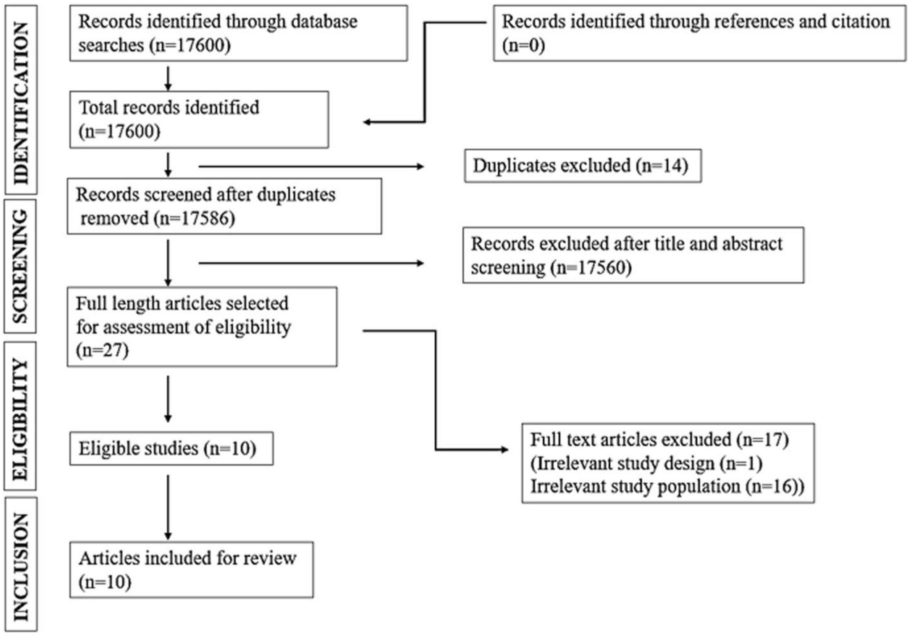

Fig. 1 PRISMA flowchart for the selection process of articles included in the review

Abilities in 1 study, Working Memory Test Battery for children in 2 studies and Kaufman Assessment Battery for Children II in 1 study were used to assess AWM. Typically developing normal-hearing children were selected as the control group in 6/10 studies and 4/10 of the included studies had no control group. Detailed characteristics of the articles included in this study are included in Table 1.

Quality assessment

'The Critical Appraisals Skills Programme' for diagnostic test study (CASP) was used to assess the quality of the studies. It consists of 12 questions to assess the article across each section to reduce bias. On analysis, it was found that all the studies were of good quality. The research questions were addressed, and there was a comparison with the reference standard in all the studies. The status of the test population was provided in detail in all studies included. All the patients received the diagnostic and reference standard tests in s10/10 studies. The test procedure was explained in detail in 9/10 studies. The results of 9/10 studies are explained so they can be calculated and worked out. The sensitivity and specificity of the tests were not provided in any of the studies, while the confidence limits have been provided in 8/10 studies for individual tasks.

Discussion

Assessment procedures

Wechsler intelligence scale for children-III

WISC-III measures cognitive functioning and was designed for children aged 6–16 years. The digit span subtest involves the child repeating progressively larger lists of digits (Wechsler 1991). Harris et al. [10] used Digit Span Forward (FDS) and Digit Span Backward (BDS) tasks. The forward task requires participants to repeat a list of random digits starting with a two-digit sequence ranging from 1 to 9. Two items are to be repeated for each sequence, and if the subject repeats no less than one of them correctly in each series, the length of the sequence is increased by one digit. Except for the change in order, the backward task is the same as the forward task. AuBuchon et al. [1] used the same procedure in their study and compared raw scores with WISC-III norms.

Forward digit span and backward digit span

Javanbakht et al. [12] used forward and backward WM to assess WM. In the FDS test, the child had to repeat a series of numbers that started with 2 digits and expanded to 7 digits, in order after they were presented. The test ends on 2 incorrect series. The number of series accurately memorized is used to grade performance. The backward digit span test is administered the same way, except the individual must repeat the numbers backward. Binaural mode scoring was done.

Table 1 Study characteristics of the selected articles

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Stiles et al. [16]	Comparative study	To study the disturbances in WM, and its relation to the receptive vocabularies in mild to moderately severe SNHL children.	Experimental group: 16 children (mild to severe SNHL) fitted with bilateral hearing aids. Mean age: 3;92 [years; months]) Control group: 24 normal-hearing children (13 boys, 11 girls) Mean age: 9;94 [years;months)	FDS BDS	FDS task: Children had to repeat the digits in the same order as presented. Numbers were presented in every 1-s interval. The digits were not repeated within the series. Additionally, "7" was omitted from the presentation to make all of them to be monosyllabic in nature. Children repeated two strings at each length. The three-digit sequence was tested first. The number of digits per sequence increased by one digit if any of the 3-digit strings could be correctly repeated. This gradual lengthening of the sequence persisted until either the children reached the string limit of 8 digits, the examiner stopped the process, or both strings of a single length were wrongly repeated back. BDS task: Children had to repeat the digits in reverse order of presentation. Except for starting with strings of two digits rather than three, test administration was the same as for FDS. The BDS task was administered similarly to the FDS task. Four different conditions were used to administer the FDS and BDS: auditory quiet, auditory noise, visual quiet, and visual noise	HI children and CNH showed an auditory advantage in forward span. HI children showed a similar memory span as that of CNH. The presence of background noise did not affect performance in either group.	Children with moderate to moderately severe HL displayed a resilient WM system. Relationships between WM and vocabulary were observed for all children; those with poor WM demonstrated a smaller vocabulary size. The presence of noise did not affect the performance of the digit task. This could be explained by the fact that either the background noise wasn't distracting enough to need a change in the executive resource allocation for the WM activities, or the resources required to decode the signal in noise are unrelated to those used for WM tasks.

Table 1 (continued)

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Harris et al [10]	Longitudinal study	To investigate how verbal STM and WM function as a developmentally limiting source of variability in children's speech and language outcomes longitudinally following CI.	Experimental group: 66 children with CI Age range: 7–15 years (Mean/SD not specified)	WISC-III Edition	The test involves the child repeating progressively larger lists of digits presented by the experimenter using live voice. Roughly one digit per second was presented. There are two recall conditions in the task: • DSF • DSB In order to complete the DSF task, participants must repeat a series of random digits, starting with a two-digit sequence and going in order from 1 to 9 (inclusive). For each sequence length, two things are presented, and if the subject reproduces at least one of them correctly, the sequence length is increased by one. This process continues until the participant repeats both of the wrong items at the same sequence length. The only difference between the DSB and DSF tasks is that subjects must reproduce the sequences in reverse order.	Compared with the normative mean scores (Population means: 10; SD: 3), the CI children's scores were 1 SD below the normative in 50.5% in DSF and 44.0% in DSB across all ages. However, the DSF and DSB performance slopes in the CI group that represented the development of verbal STM/WM capacity were comparable in magnitude to values found in a sample of people with normal hearing using WISC-III cross-sectional norms.	Variation in STM/WM is one of the fundamental neurocognitive-related factors that underlie all behavioral measures of S/L performance.

Table 1 (continued)

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Soleymani et al. [15]	Cross-sectional study	To investigate WM as a cognitive ability in children with ND and CI.	Experimental group: 50 children with CI. Age range: 5–7 years Mean: 6.16 SD: 0.79 Control group: 50 children with ND. Age range: 57 years Mean: 6.16 SD: 0.79	NWR FDS BDS	Non-word repetition task Two practice non-words were given to the children before moving on to the actual testing. Children were presented with the original target non-words, which they had to repeat. They received a score of 1 if they repeated the target non-word perfectly; otherwise, they received a score of 0. The total score for this task was 25. FDS and BDS tasks The child was told to repeat seven sets of numbers, 3–9 for FDS and 2–8 for BDS. In FDS, children were tasked with repeating the numbers in the exact same sequence as before. Children should just tell numerals in reverse order in BDS, though. Each number in the series was stated with a one-second interval. Every group of numbers is repeated twice. Each response was worth one point when it was correct. The task was concluded after two attempts at each sequence failed. The maximum score for each task was 14. The FDS was finished before the BDS.	Mean and SD • FDS NH: 5.42 (1.63) CI: 2.30(1.43) • BDS NH: 3(1.95) CI: 0.84(0.84) • NWR NH: 22.78(1.59) CI: 12.28(1.82) The NWR scores of the CI children showed a strong relationship with the FDS and BDS. Also, FDS and BDS are strongly associated. Although FDS and BDS were substantially correlated, the NWR scores of the ND children were shown to be only modestly related to them.	The working memory of children with CI has been compromised. The existence of differences between ND and CI children suggested that early exposure to sound had a significant impact on the part of the brain that stores and retains phonological information in STM. Children with CI were found to have similar developmental patterns. In the BDS, there was no discernible difference between preschool and first grade. Children with CIs may not perform as well on BDS in the early stages of development as with ND since it is a test designed to evaluate complex memory spans.

Table 1 (continued)

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Tao et al. [18]	Correlational study	To study the relationship between AWM and speech perception performance in Mandarin-speaking CI children.	Experimental group: 32 CI users (21–pre-lingual HI 11–post-lingual HI) Age range: 6.0–26.0 years Mean: 13.0 SD: 4.0 Control group: 21 normal-hearing children Age range: 8–14 years Mean: 11.0 SD: 1.6	Auditory digit span test	An adaptive (1-up/1-down) approach was used to test auditory digit span recall in both the forward and backward directions. The stimuli featured a single man talker uttering the numbers 0 through 9. Numbers were chosen and delivered in random order (no visual cues). Children replied by clicking on the response boxes displayed on a computer screen in the order of the sequence of digits they heard. Three digits made up the first series. The number of digits provided was either increased or decreased depending on how accurately the response was given.	The mean score CI group: BDS: 4.72 (SE = 0.33) FDS: 6.10 (SE = 0.35) for. NH group: BDS: 5.96 (SE = 0.30) FDS: 7.39 (SE = 0.21) Performance ranged from 1.8 to 11 for FDS and from 2.1 to 9.7 for backward digit span, indicating a significant inter-subject variability. Only sentence recognition in quiet environments showed a significant correlation with AWM efficiency. The relationship between WM and lexical tone recognition was not observed.	Compared to NH participants, CI individuals' scores on the forward and backward digit span were significantly lower. Despite some similarity in the distributions of digit span scores, Mandarin-speaking CI individuals may be less capable and efficient at processing phonological information than NH participants, which would show up in their digit span. The connection between WM and speech performance was unaffected by pitch cues.
Torppa et al. [19]	Longitudinal study	To investigate the effects of musical experience, auditory working memory, and F0 auditory discrimination in the CI group.	Experimental group: 21 unilaterally implanted children (CIm and CIn group) Control group: 21 normal-hearing children. All the children were aged 4–13 years	FDS	ITPA FDS task was employed. In the analysis, raw scores were employed; these don't necessarily indicate how many digits are repeated.	Mean scores and SD in FDS task: NH-T1 = 22.43 (7.10) NH–T2 = 25.43 (7.72) CIm-T1 = 20.38 (7.61) CIm-T2 = 24.38 (9.52) CIn-T1 = 15.69 (5.30) CIn-T2 = 16.77 (5.83) FDS in Cim and NH group were similar, but CIn group performed more poorly. Similar findings were seen with respect to F0 discrimination and prosodic perception.	Children with CIs who have musical practice do better on the FDS than children without musical experience. Digit span and intensity perception were correlated to prosodic perception.

Table 1 (continued)

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Willis et al. [20]	Longitudinal study	To compare verbal and visual WM of six children with congenital HI.	Experimental group: 6 children/adolescents with a unilateral cochlear implant Age range: 8 and 15 years	Subtests of WMTB-C	Children are asked to recall words in the same order as presented in the word recall subtest. The NWR followed the same procedure, and the items followed a similar CVC structure as the "real" word. Four targets must be correctly recalled by the children. The difficulty of the tasks increases for each subgroup starting at two, three, or four. The subtest is terminated when a child is unable to correctly reproduce four targets from a subset.	Mean standard scores: first-year of study Word recall: 81.67 (SD 12.48) Non-word recall: 110 (SD 10.66) Second-year of study Word recall: 80 (SD 13.19) Non-word recall: 108 (SD 11.28) Performance in non-word recall was better than word recall at both points of measurement.	For 2 years, all the children displayed the same pattern of verbal working memory. It was found that the children had more trouble with non-word memory than they did with word recall. Children with HI may not have appropriate phonological representations in their STM, which would make storing and retrieving information more challenging. Visual WM was comparable to that of peers with average hearing.
AuBuchon et al. [1]	Longitudinal study	To study whether early-implanted, long-term CI users exhibit delays in verbal STM and WM capacity when audibility and speech production processes are excluded.	Experimental group: 23 CI users The age range at initial testing: 7.8–15.3 years (Mean 11.8; SD 1.9) Age at follow-up: 10.1–17.1 years (Mean 14.0; SD 2.4) Control group: 23 NH controls Age range at initial testing 8.2–15.3 years (Mean 12.5; SD 2.2) Age range at follow-up: 10.1–16.6 years (Mean 14.0; SD 2.1)	WISC-III subsets	Lists of the set of digits were presented using live voice as per the instructions for the forward and backward span subtests of the WISC-III. The lists were to be repeated aloud by the participants in either forward or reverse order.	Forward span measures: A significant effect of hearing status was seen across forward-span measures. CI group mean 6.47 (SD 2.72) NH group mean 8.3 (SD 3.25) Significant effects on tasks were also seen. ADS-F mean 8.25, SD 2.76 No interaction between hearing status and task. NH group had a superior performance than CI users on all forward tasks. Backward span measures: No effect on hearing status was seen Effect of task was seen ADS-B mean 5.18, SD 2.14 No interaction between hearing status and tasks.	The performance on ADS-F had a strong positive correlation with a visual and computerized version of the digit span-forward task (no auditory stimuli were given) in long-term CI users. While ADS-B did not correlate with the other 2 tasks. Also, the performance in ADS-B did not vary between the NH and CI groups as there was an increase in demand for processing the instructions.

Table 1 (continued)

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Bharadwaj et al. [3]	Cross-correlational study	To study the WM and STM skills in the auditory and visual modalities in school-going CI children. Study the relationship between verbal and visual WM/STM measures versus reading.	Experimental group: 10 children Age 7 to 11 years (Mean/SD not specified) CI users	WJ III COG NU KABC-II	In the Numbers Reversed task, the test subject responds to a series of numbers before repeating them in a reverse manner. AWM is a task that assesses a person's capacity to hold a list of words and numbers in immediate awareness and then reorganize the information so that the words are remembered first and subsequently the numbers. The Number Recall task tests a subject's ability to retain auditory short-term information by having them listen to a set of numbers before having them repeated in the very same order. The Word order task requires the participant to touch the object's silhouettes after hearing their names in the same order.	The mean standard scores on WJ III COG NU (numbers reversed and AWM) were less than the average SD (scores were < 85 in both numbers reversed and AWM). Reading measures and the number recall test showed a strong positive association (except for passage comprehension and oral reading).	All CI children exhibited less than average performance in tasks related to verbal knowledge (number recall, word order) in KABC II. The outcomes are consistent with the idea that early-onset hearing loss impacts capacities like memory and creating sequential information due to sensory deprivation. The abilities were related to the following: Word reading abilities–Auditory STM Passage comprehension abilities–Visual and Auditory WM.
Talebi, S., and Arjmandnia, A. A. [17]	Non-experimental, correlational, and causal-comparative study.	To study the interaction between WM and STM performance and their impact on CI outcomes	Experimental group: 31 CI children Mean age: 121.52 months; SD: 19.946 Control group: 31 NH children Mean age = 120.68 months; SD = 18.137	WMTB-C	Not explained in detail.	Working memory scores (Mean (SD)): NH: 68.9 (10.67) HI 57.13 (8.64) Working memory span: NH 4.09 (0.65) HI 3.61 (0.48) Short-term memory score NH 56.13(6.96) HI 47.10 (6.57) Short-term memory span: NH 4.63 (0.62) HI 3.87 (0.55) WM efficiency was significantly and positively correlated with CI results. In addition, the children with cochlear implants performed worse than their counterparts with normal hearing.	Children with and without cochlear implants were found to have WM and STM that interacted well with each other. Working and short-term memories are enhanced in people implanted at younger ages. There is a substantial correlation between AWM and STM, as well as between AWM, STM, and speech intelligibility.

Table 1 (continued)

Author and Year	Study design	The objective of the study	Population type	Tests used	Test procedure	Results	Discussion
Javanbakht et al. [12]	Cross-sectional study	To compare the memory abilities of two groups of children who used hearing aids in both ears and only differed in their capacity to understand speech in noisy environments.	Experimental group: 31 hearing aid user students Participants were split into 2 groups: • HP-BKB SIN score Less than or equal to 7 • LP- BKBSIN score greater than 7 Age range: 8–12 years were selected Mean and SD 9.13 ± 0.17	FDS BDS NWR (Persian version)	FDS: The number series started out with two digits and eventually progressed to seven digits. The number of correctly memorized series is how the performance is measured. The exam was terminated after the child stated two wrong series. BDS: Similar to that of FDS, except the subject must repeat the numbers backward. Non-word repetition test: 40 non-sense syllable words. Each non-word contained 2, 3, or 4 syllables, and the interval between each presentation was 10 s or shorter, depending on how quickly the participant repeated each item. The test was carried out with a human voice and was based on the phonetically transcribed non-words that were accessible. The child hears the non-sense words read aloud, and he or she must repeat them. The number of correctly repeated non-words is used to grade performance.	Mean WM scores: FDS: HP-2.00 (± 0.50) LP-1.52 (± 0.65) BDS: HP-2.00 (± 0.50) LP-1.52 (± 0.68) NWR: HP-28.77 (± 5.04) LP-22.33 (± 4.21) The LP group had poor scores on FDS, BDS as well as NWR tests.	Speech in noise tests was significantly correlated with all the WM measures. This correlation was higher for NWR than for FDS and BDS.

Abbreviations: *HI* Hearing impaired, *CI* Cochlear implant, *NH* Normal hearing, *ND* Children with normal development, *WISC—III* Wechsler Intelligence Scale for Children-III, *DSF/FDS* Digit Span Forward, *DSB/FDB* Digit Span Backward, *NWR* non-word repetition, *WJ III COG NU* Woodcock-Johnson III Tests of Cognitive Abilities, *KABC–II* Kaufman Assessment Battery for Children II, *ITPA* Illinois Test of Psycholinguistic Abilities, *CIm* CI with musical experience, *CIn* CI without musical experience, *T1* The first measured time point, *T2* the second measured time point, *WMTB-C* Working Memory Test Battery for Children, *WM* Working Memory, *AWM* Auditory working memory, *STM* Short-term memory, *LP* Low performance, *HP* High performance, *BKBSIN* Persian version of Bamford-Kowal-Bench Speech In Noise test, *SNHL* Sensorineural hearing loss

Soleymani et al. [15] used a set of seven numbers, i.e., 3–9 for forward and 2–8 for the backward digit span test. Every set of numbers appeared twice, and there were no repeated digits in a string. Each correct response was worth one point, with the maximum score being 14. The task terminated after two failed sequences.

Stiles et al. [16] performed the FDS and BDS tests in quiet and noise conditions. The digits were presented at 65dB SPL in the auditory mode through a monitor-mounted speaker at an angle of 0° and 0.5 m distance in the quiet. In the noisy conditions, the background noise was given from two speakers at ± 110° azimuth at a 1-m distance. In noisy conditions, the stimuli were presented at + 15 dB SNR as this level was considered a good SNR for classrooms, according to ANSI (2002). Each item in a trial is worth 0.5 points. The FDS score was calculated using the formula – 2 + 0.5 * (number of correct responses), while the BDS score was calculated using the formula – 1 + 0.5*(number of correct responses).

Tao et al. [18] used digits 0–9 in auditory-only mode using an adaptive approach (1-up/1-down) to test auditory digit span recall in both the forward and backward directions. The test began with 3 digits initially, and the sequence length was increased based on the number of correct repetitions. The first two trials were adjusted by 2 digits, while the remaining by 1 digit. Twenty-five trials were carried out in each run. The digit span score is the mean score of all trials except for the first two trials.

Illinois test of psycholinguistic skills-FDS

ITPA is used for children aged 4–8 years to assess their capability to acquire and use language. Torppa et al. [19] used the FDS subtest of the ITPA to assess the WM. The analysis employed raw scores, which do not accurately reflect the number of repeated digits. The FDS was conducted using the live voice of the experimenter in a face-to-face setting.

Non-word repetition

In the present review, two studies used the non-word repetition test. Soleymani et al. [15] developed the material for the NWR test. Sixty words in Farsi were chosen and each word's one or two phonemes were altered, turning it into a non-word with no Farsi-language meaning. A team of five speech-language pathologists and five linguists were assembled to choose appropriate non-words from the list. Twenty-five non-words met the 90% threshold.

Javanbakht et al. [12] used the Persian version of the NWR test. This test contains 40 non-sense words, and each had 2, 3, or 4 syllables. Based on the repetition speed following each item, the interval between each item presentation was around 10 seconds or shorter. The child had to listen and repeat them exactly. The number of non-words repeated correctly was used to grade performance.

Woodcock-Johnson III tests of cognitive abilities

It is a test to assess cognitive ability and cognitive assessments in children above age 2 through adulthood. Bharadwaj et al. [3] used the task known "numbers reversed" and "AWM" tasks from this tool. The AWM range measures include the ability to reverse numbers and AWM. The numbers presented have to be repeated in reverse order. In the AWM task, the participant is presented with a list of words and numbers, and the participant reorders the information by recalling the words and then the numbers.

Working memory test battery for children

The WM of children between the ages of 5 and 15 can be tested using the Working Memory Test Battery for Children (WMTB-C). The word recall and non-word recall subtests measure how well the phonological loop functions. Children must recall single-syllable words in the order they were given. The method is the same for the non-word recall subtest, and the items have the same structure as the actual words. The subtests forbid-multiple attempts. In order to control for the oro-motor deficiency as a potential confounding factor, children were instructed to repeat single-syllable and CVC nonsense words. In this review, two studies used WMTB-C to assess WM.

Kaufman assessment battery for children II

KABC-II is a test employed for children between 2.5 and 12.5 years, which offers a global intelligence assessment. Bharadwaj et al. [3] used the subtests 'Number Recall task' to evaluate auditory STM capacity by repeating the numbers in a given order and 'Word Order task' to test auditory STM by touching the silhouettes of those objects when heard.

The efficiency of the measures of auditory working memory

The efficiency of the test used in the reviewed articles has been explained through the correlation of the AWM performances with auditory, visual, and verbal measures.

Stiles et al. [16] examined the vocabulary and WM in children with mild to moderately severe HL (Hearing Loss). Phonological bias and auditory advantage were found in children with HL. Children with HI could recite longer strings of the stimulus presented. This ability was found to be better in auditory modality than in visual modality in HI children suggesting the underlying mechanism for auditory advantage is actively present in them.

The articulation rate in children with HI was comparatively slower than in normal hearing(NH) children suggesting the reduced efficiency in the subvocal articulatory system in the WM. The Corsi span used to assess the visuospatial STM was similar between NH children and children with HI with high executive function. In the auditory-quiet condition, they did better on the digit span. The presence of low-pass random background noise did not impair CNH or CHL's working memory performance in a controlled setting with highly predictable stimuli. The authors concluded that in children with HI, WM under challenging situations could be best administered with less predictable sentences and speech-like noise in the background.

Harris et al. [10] examined the influence of verbal STM and WM capacity as a factor on children's speech and language results following cochlear implantation. This study found that verbal STM and WM capacity process assessments accurately predicted long-term speech and language outcomes following cochlear implantation. Compared to normative data the maturation speed is slower than that of verbal STM/WM. In the long term, the baseline data showed a stronger association with speech and language outcomes than the measures at further visits on the digit span. The authors necessitate the need for integrating these results with a wider range of verbal and visuospatial STM/WM measures in the future in order to provide a more complete picture of each child's capacity for information processing. This is due to the results of this study being based solely on DS as a measure of verbal STM/WM.

Soleymani et al. [15] investigated the WM in normally developed children and children using CI between 5 and 7 years and found that some WM components are impaired in CI children. CI children with early exposure to sound significantly impacted the human memory system employed for phonological information stored and retained in STM. This study indicated that children implanted later in life had lower NWR, FDS, and BDS scores suggesting that exposure to auditory input improves a child's performance on phonological processing tasks. The absence of standardized tests apart from the NWR test is one of the limitations of this study.

Tao et al. [18] investigated the relationship between AWM and speech perception in Mandarin-speaking children with the CI. For all speech parameters (Word in sentence recognition (quiet and noise), Chinese disyllable recognition, and Chinese lexical tone recognition), CI users dramatically underperformed NH listeners regarding speech performance. The worst CI performance was for noisy sentence identification.

Despite the considerable overlap in digit span score distributions, CI individuals' FDS and BDS scores were worse than those of NH participants. Additionally, CI participants' articulation rate was substantially slower. In both CI and NH subjects, there was a strong correlation between the FDS and BDS scores and between the articulation rate and digit span scores. However, WM tests did not significantly correlate with CI users' ability to recognize sentences in noise.

Torppa et al. [19] used the ITPA-FDS subtest to assess AWM in children. It was found that AWM interfered with pitch perception, wherein the CI children with music exposure had comparable performance to the control group. Longer forward digit spans improved performance on both prosodic measures. F0 discrimination and FDS showed similar developmental trends.

Willis et al. [20] used the word and non-word recall subtest from WMTB-C to assess verbal memory and the odd-one-out subtest from the Automated Working Memory Assessment. Findings indicate that despite long-term usage of CI or hearing aids, the population of children with HI has extremely low spoken language outcomes. All six study participants outperformed the control group when challenged to recite lists of non-words rather than actual words. The results suggest that these children may struggle to access their lexicon and retrieve words because they had a tougher time repeating words than non-words. It has been suggested that children with HI might not have enough phonological representations in their STM, making storing and retrieving knowledge more difficult. CI users had visual memory abilities on par with those of their hearing peers. The study's findings also highlight the requirement for specialized memory tests that take into account the evolving needs of children with HI memory impairments. The standard NWR task only draws attention to the fact that children with HI have trouble with the task itself because of their perceptual issues. Hence, the authors suggest the use of an alternative NWR test in combination with other measures of STM and WM.

AuBuchon et al. [1] used auditory(ADS), visual(VDS), and computerized (CDS-auditory digit span task using visual representation) digit span tasks. Higher receptive vocabulary, non-verbal IQ scores, and an earlier age of deafness onset were all associated with ADS-F for CI users. In contrast, CDS-Forward was strongly connected to receptive vocabulary and the length of CI use, while VDS-Forward was significantly related to receptive vocabulary. The duration of CI use is highly correlated with both backward-span tasks. Additionally, ADS-Backward and CDS-Backward correlated with non-verbal IQ and receptive vocabulary, respectively. The authors concluded that fundamental cognitive processes that underlie STM are impaired rather than problems with speech production or audibility in long-term CI users. Average delays were longer for CI users, providing them more time to take advantage of age-related memory performance increases. The authors also concluded that while forward and backward digit spans are helpful clinical instruments for evaluating CI users' short-term and working memory capacity, these traditional actions using immediate memory are inadequate to further understand the comprehension of the fundamental memory systems taken into consideration here.

Bharadwaj et al. [3] examined auditory and visual WM and STM in children using CI. The KABC-II, WISC-IV Integrated, and the WC III COG NU were used to measure verbal knowledge, auditory and visual STM and WM, and verbal knowledge in general. The Woodcock Reading Mastery Test III was used to evaluate reading performance. The results show that CI users' performance on the auditory STM measures was below average. This is consistent with the idea that WM ability in children with early-onset HL is modality-specific. The advantages of visual WM tests suggest the existence of modality-specific subsystems. Children with CI performed below average on reading evaluations for listening and passage comprehension. These measures were related positively to visual STM, visual WM, and auditory STM.

Talebi and Arjmandnia [17] investigated how WM and STM interact with auditory perception and speech understanding in children with CI and compared the WM and STM in children with CI and NH groups. WMTB-C was used to assess memory performance, Categories of Auditory Performance was used to assess auditory perception, and Speech Intelligibility Rating to evaluate speech production. Children using CI performed poorer than their NH peers in WM and STM. Children with and without CI had similar levels of WM and STM. The results showed a positive and substantial relationship between the WM and STM of children with CI and their auditory perception. Additionally, there was a positive association among children with CI between WM and STM and speech understandability.

Javanbakht et al. [12] compared the WM capacity as a factor influencing speech in noise performance in NH children and children using a hearing aid. This study's working memory tests were compared to the results of the speech-in-noise perception test. It became clear that there was a strong relationship between the results of WM tests and the speech-in-noise perception scores in children with HI. The test employed in this study makes it more challenging to determine the forward and backward digit span than the conventional tests because of the stimuli utilized, which are non-sensical pseudo-words with many different syllables, that involve different levels of complex cognitive and auditory processing, such as working memory, phonological processing, auditory decoding, and the executive planning unit of the motor part of speech.

Conclusion

This systematic review has described the working memory measures available and the results in children with HI. The assessment tools focused chiefly on the auditory (and verbal) WM and STM. The present study shows that the digit span task, though used to assess WM, focuses on the memory span rather than the working memory itself. Yet, it is the most commonly used form of working memory measure. Apart from the digit span tasks, word and non-word recall, number reversing, and non-word repetition are the most frequently employed measures.

The most common memory assessments, such as forward and backward digit spans fail to provide comprehensive knowledge of basic memory mechanisms. According to the present review study, the FDS task is more sensitive than the BDS task as it requires more effort to comprehend the instructions. As a result, it highlights the necessity of reviewing WM literature in search of novel experimental strategies and behavioral tasks that can more precisely detect weaknesses in phonological storage and lexical processing. Furthermore, it is necessary to describe the verbal and linguistic processing abilities used by children with HL.

Compared to the tests for detecting the FDS and BDS, the non-word repetition test is more complex as it consists of meaningless pseudo-words with various syllables. Also, using monosyllabic non-words overcomes the potential disadvantage of perceptual difficulties in the pediatric population. It is also indicated that children with severe to profound HL have poorer performance in all the working memory tasks despite being fitted with amplification devices (hearing aid/CI). In contrast, children with mild to moderately severe HL demonstrated performance similar to their peers in digit span tasks in quiet and noise conditions. As a future direction, focus on developing deficit-specific assessment measures of AWM, and the normative data for the same has to be considered.

Limitations

More number of studies included participants with cochlear implants, and very few studies had hearing aid users. Therefore, the precise information about auditory working memory outcomes in hearing aid users could not be explained.

Abbreviations

HI	Hearing impairment
CI	Cochlear implant
NH	Normal hearing

ND	Children with normal development
WISC-III	Wechsler Intelligence Scale for Children-III
DSF/FDS	Digit Span Forward
DSB/FDB	Digit Span Backward
NWR	Non-word repetition
WJ III COG NU	Woodcock-Johnson III Tests of Cognitive Abilities
KABC-II	Kaufman Assessment Battery for Children II
ITPA	Illinois Test of Psycholinguistic Abilities
CIm	CI with musical experience
CIn	CI without musical experience
T1	The first measured time point
T2	The second measured time point
WMTB-C	Working Memory Test Battery for Children
WM	Working memory
AWM	Auditory working memory
STM	Short-term memory
LP	Low performance
HP	High performance
BKBSIN	Persian version of Bamford-Kowal-Bench Speech In Noise test
SNHL	Sensorineural hearing loss

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