The cognitive effects of noise on the memory performance of children with cochlear implants

Barbara Arfé[1,2,3], Gaia Spicciarelli[4], Flavia Gheller[2], Massimiliano Facca[1], Nadina Gómez-Merino[5], Patrizia Trevisi[3,4], Alessandro Martini[3]

[1]Department of Developmental Psychology and Socialisation, University of Padova, Padova, Italy
barbara.arfe@unipd.it; massimiliano.facca@studenti.unipd.it
[2]Human Inspired Technologies Research Center-HIT, University of Padova, Padova, Italy
flavia.gheller@unipd.it
[3]Padova University Research Center "I-APPROVE-International Auditory Processing Project in Venice", Venice, Italy
alessandromartini@unipd.it
[4]Department of Neuroscience DNS, Otolaryngology Section, University of Padova, Padova, Italy
patrizia.trevisi@unipd.it; gaia.spicciarelli@unipd.it
[5]Department of Developmental and Educational Psychology, University of Valencia, Valencia, Spain
nadina.gomez@uv.es

Abstract

Concentrating to perform cognitive tasks in a noisy environment requires to re-allocate mental resources to overcome the interference of noise. This process and the resulting fatigue, i.e., cognitive effort, can be detrimental to hearing children's cognitive performance and ultimately to their learning. However, we know little of how background noise affects the cognitive performance of children with hearing loss. In a pilot trial, we addressed this research question. Eight cochlear implanted (CI) children and 5 age-matched normally hearing children (NH) (7-12 years) carried out an auditory attention task and a digit span task in quiet and babble noise. Behavioral (accuracy), self-report, and psychophysiological (pupil dilation) measures were used to assess children's cognitive performance and cognitive effort. CI children performed worse than NH children in both acoustic conditions. However, no significant effects of acoustic condition (quiet/noise) were observed. Although CI children efficiently compensated for noise in performing the cognitive tasks, their pupil dilation revealed greater cognitive effort in noise than in quiet.

Keywords: noise, cognitive effort, working memory, cochlear implants, children.

1 Introduction

Most of children's everyday activities, including learning in a classroom, occur in noisy and reverberating environments. Children's ability to compensate for the interference of noise and stay focused on task represents thus a foundational skill for their cognitive development and learning attainments [1, 2, 3, 4, 5]. Surprisingly, we know very little of how children can adapt their cognitive performance to these noisy environments [3]. Understanding how noise interferes with the cognitive functioning of a child is important, particularly when children with developmental vulnerabilities or sensory deficits (like hearing loss) are concerned [6, 7].

Concentrating to perform cognitive tasks in a noisy environment requires to re-allocate mental resources to overcome the interference of noise. This re-allocation process and the resulting fatigue (cognitive effort) experienced during tasks in noise can be especially detrimental to the cognitive performance of children who already face greater cognitive and perception difficulties, with consequences also for their learning. Unfortunately, the studies conducted with these special populations are still scarce. As a result, also our understanding of the compensatory mechanisms of these children is limited. To address this literature gap, in this study we explored how compensating for background noise during a memory task affects the cognitive effort and memory performance of children with congenital hearing loss (HL).

Noise in learning environments such as classrooms can be the effect of external environmental sources (e.g., traffic or aircraft noise) or indoor sources (classroom noise, including background speech). However, background speech seems generally more impactful on children's speech perception [8] and learning performance [9] than environmental (e.g., traffic) noise, because more strongly influenced by informational masking mechanisms. Informational masking occurs when the masking input is meaningful or intrinsically relevant for the individual, and hence competes for the limited attentional resources of the listener [10]. The interference generated by informational masking seems strong especially for verbal learning tasks involving vebal working memory processes, such as spelling and reading [9], and occurs also when the mask is unintelligible (like with unintelligible background babbling) [11].

The disruptive mechanisms of irrelevant speech on speech perception or cognitive performance are also referred to as the *irrelevant-speech-effect* (ISE) and have been documented both in adults and children, especially with regard to serial recall tasks [12]. Verbal short-term/working memory and the serial recall mechanisms of these memory systems are foundational cognitive processes, with a broad impact on children's cognition [13], language development [14], and learning [15]. Investigating the ISE on children's verbal short-term/working memory represents thus an important target of cognitive and hearing science alike [12]. However, attempts to study this phenomenon with children with HL have been rare so far.

Working memory (WM) is a limited capacity system used when individuals need to retain information for later recall while they are also engaged in additional processing of that (or other) information [16]. The storage and processing of information within WM share the same mental resources, thus individuals are worse at encoding and storing information in WM when extra mental resources are required for processing the material (i.e., try to recall one or more words in a sentence while processing the next one in a text). One of the most widely used tests to assess verbal short-term and WM with children with HL is digit span [15, 17]. The test consists of two subtest conditions: forward digit span, based on immediate recall of a sequence of auditory presented digits, and backward digit span, based on immediate recall of a sequence of auditory presented digits in reverse order (i.e., backward). While the first subtest condition provides a measure of verbal rehearsal skills, that is, the ability to temporarily maintain a series of items in verbal WM through subvocal repetition [17, 18, 19], the second taps executive control processes, or the ability to allocate mental resources between cognitive tasks, such asactively maintaining a sequence of items in memory (storage) while operating on them (processing).

In verbal memory tasks, the ISE seems to occur because of an automatic intrusion of the irrelevant speech fragments into the phonological short-term memory store,or phonological loop, used to record and recall serial information through verbal rehearsal [20, 21]. Individuals with better WM abilities are typically better at exerting cognitive control over their performance and (re)allocate cognitive resources, and these abilities should also lead to better control of interference of irrelevant stimuli on WM [22, 23]. However, several studies have reported no association between adult and children's WM and the magnitude of the ISE [20, 24], and in few cases even evidence of an opposite relationship, finding that adults and children with higher WM skills demonstrate in fact larger ISEs, or susceptibility to the speech interference, in comparison to individuals with lower WM [12]. This seemingly counterintuitive finding could be explained by the high-WM individuals' larger use of verbal rehearsal strategies to perform serial recall tasks . Rehearsal is indeed a highly efficient strategy for enhancing serial recall, but a mostly inefficient strategy when the goal is to recall lists of stimuli in the presence of speech interference [12].

Children with congenital hearing loss (HL) typically show poorer verbal WM and poorer use of verbal rehearsal strategies in comparison to their hearing peers [15, 17], although it is unclear whether they simply make less use of subvocal rehearsal than hearing children or are rather unable to use rehearsal processes efficiently [25]. In both cases, if the origin of the ISE is an interference at the level of verbal rehearsal [12], we should expect a smaller ISE in these children than in normally-hearing children. In the present study, we tested this hypothesis by comparing children's performance in forward digit span and backward digit span tasks in quiet and noise (multi-talker babbling) conditions. Differently from previous studies [7], we not only examined how CI children's performance varied with noise but also assessed their cognitive effort in quiet and noise by recording their pupil dilation, a psychophysiological measure of cognitive fatigue. Pupillometry has become increasingly popular in hearing and psycholinguistic research as a measure of real-time fatigue associated with the cognitive workload in a task [26]. In the present study, it was used to account for the cognitive overload experienced by children performing WM tasks in noise.

2 The Study

The study tested the effect of background speech (multi-talker babbling) on the verbal WM performance (digit span forward and digit span backward) of eight children with cochlear implants, compared to a control group of five age-matched normally hearing peers. Behavioral, self-report and pupil dilation measures were used to explore differences in the ISE between the two groups.

2.1 Participants

Thirteen children, 8 cochlear implant (CI) users (7 boys and 1 girl) with a congenital hearing loss, and five normally hearing (NH) controls (2 boys and 3 girls) participated in the study. The two groups were matched on age (CI children's mean age = 9.63, SD = 1.60 and NH children's mean age = 9.40,SD = 1.14; age range 7-12 years). Participants' characteristics are reported in Table 1. All CI users had a diagnosis of sensorineural profound hearing loss. Most of them received an early compensation (≤18 months of life) and their first implant before the age of three years. Five children were fitted with bilateral implants. No disabilities or behavioral problems were reported for the CI users or the NH children, although three CI users performed below age norms on the digit span (see age-corrected scaled scores in Table 1).

Table 1. Participants' characteristics (digit span scores below age norms in bold)

Group	Age	Sex	Etiology	Age at first compensation (months)	Age at CI fitting (years)	CI (side)	CPM (percentile score)	Digit span age-corrected scaled scores
CI	11	M	CMV	7 (BIL hearing aids)	3.5	R	74	**4**
	12	M	Unknown	Unknown	2;7	SEQ BIL	63	7
	11	M	CX26	18 (BIL hearing aids)	2;3	SEQ BIL	42	12
	7	F	CX26	Unknown	1.5	SIM BIL	76	8
	9	M	Unknown	36 (BIL hearing aids)	5	L	82	9
	9	M	CX26	3 (BIL hearing aids)	1;2	SEQ BIL	66	**3**
	9	M	CX26	8 (BIL hearing aids)	2;4	SEQ BIL	32	6
	9	M	EVA	18 (L hearing aid)	2	R	39	**5**
NH	9	M	-	-	-	-	100	14
	10	M	-	-	-	-	88	6
	11	F	-	-	-	-	46	9
	10	F	-	-	-	-	82	10
	9	F	-	-	-	-	88	11

Note: BIL= Bilateral; SEQ BIL = sequential bilateral; CPM = Coloured progressive matrices; CMV = Cytomegalovirus; CX26 = connexin 26; EVA = Enlarged Vestibular Aqueduct; BIL = bilateral; SEQ = sequential; SIM = simultaneous; R = right; L = left

2.2 Methods

All participants performed the following tasks:

- *Coloured Progressive Matrices test* [27, 28]. The test, designed for use with children, provides a measure of non-verbal intelligence. Children are asked to choose the missing element from six options to complete a pattern of drawings. The score is the total number of correct answers, percentile scores are computed based on children's age.
- *Italian Matrix Sentence Test* [29]. This adaptive assessment test was used to estimate the SNR at which speech in background noise was correctly perceived 60% of the times. SNR was measured in free field and a fixed noise condition (noise presented at 65 dB SPL). The test was performed at the beginning of the experimental protocol.
- *Auditory attention subtest (Batteria di Valutazione Neuropsicologica - BVN 5-11)* [30]. This test was used to assess children's sustained and selective attention. Children are asked to listen carefully to a three-minute audio consisting of a word list and tap on the table only when they detect a target word (i.e. *sole/sun*).
- *Auditory Digit span (Wechsler Intelligence Scale for Children – Fourth Edition* - WISC-IV*)* [31]. It was used to assess children's verbal WM. Both the digit forward and digit backward tasks were administered to children. In the digit forward task children have to repeat sequences of digits of increasing length in the same order as they are produced by a speaker. The final score, corresponding to the number of sequences correctly recalled, is considered an indicator of the child's verbal rehearsal skills [15]. In the backward digit span task, children are asked to repeat sequences of digits backward. The length of the digit sequence increases progressively as the child progresses through the task. Performance on the backward digit span is considered a measure of the executive component of verbal working memory [19, 32]. All items were presented auditorily through a speaker.
- *Fatigue scale* [33]. This self-report questionnaire was used to assess children's perceived fatigue in quiet and noise. Children rate on a 5-point scale their perceived fatigue and distress during the task.
- *Anamnestic questionnaire* [15]. The questionnaire was administered to parents to obtain information about the etiology of the child's HL, age at implantation, type of implantation, additional disabilities, and the child's home linguistic environment.

2.2.1 Procedure

Parental informed consent was collected for all participants. All tests, except the CPM, were performed in a soundproof cabin. Children's pupil dilation was recorded by the Pupil Core binocular headset (i.e., eye-glasses) from Pupil Labs [34]. Calibration was performed first. Subsequently, baseline pupil dilation measures were collected. For each participant, the dynamic range of the pupil diameter was determined by recording the maximum and minimum diameter of the pupil in quiet, before any experimental task [35]. Baseline pupil dilation was recorded at around 110 lumens, as measured by a lux meter. Luminosity was controlled during each session and remained approximately the same for all participants.
Task order was fixed, so that all participants performed the tasks in the same order, with the only exception of the digit span task, which was performed twice. in quiet and noise, in counterbalanced order across participants. Tasks were administered in the following order:

1. Matrix Test (in noise)
2. Digit Span forward and backward (in quiet or noise)
3. Auditory Attention Test (in quiet)
4. Digit Span forward and Backward (in noise or quiet, opposite to the condition in 2.)
6. Self-report cognitive fatigue (in quiet)
7. Raven matrices (in quiet)

This research protocol was approved by the Ethical Committee for the Psychological Research of the University of Padova on the 5th of November 2019.

3 Results

Separate analyses were run on the behavioural/self-report and psychophysiological measures. Results are thus reported in two sections.

3.1 Behavioral measures

Means and standard deviations for the CI and NH participants' performance are presented in Table 2.

Table 2. Participants' performance scores: range scores, means (standard deviations in parentheses).

Tests Administered	Group	Minimum	Maximum	Mean (SD)
Digit Span Forward - Quiet	CI	4	10	6.50 (1.77)
	NH	6	10	7.60 (1.52)
Digit Span Forward - Noise	CI	4	11	6.50 (2.204)
	NH	6	9	7.60 (1.14)
Digit Span Backward - Quiet	CI	4	8	5.38 (1.41)
	NH	5	9	7.00 (2.00)
Digit Span Backward - Noise	CI	4	8	5.50 (1.31)
	NH	4	9	6.00 (2.00)
Digit Span Total - Quiet	CI	9	18	11.88 (2.85)
	NH	11	17	14.60 (2.30)
Digit Span Total - Noise	CI	9	19	12.00 (3.30)
	NH	10	17	13.60 (2.88)
Auditory Attention Test	CI	23	45	32.63 (6.68)
	NH	33	37	34.80 (1.64)
CPM	CI	23	32	27.75 (3.28)
	NH	28	35	31.80 (2.49)
Fatigue Scale Score (range 1-5)	CI	1.50	3.17	2.23 (0.64)
	NH	1.60	2.50	2.02 (0.34)

Note: CI = with cochlear Implant; NH = Normally hearing; CPM = Coloured progressive matrices

Non-parametric analyses were performed to test differences between groups (CI/NH) and conditions (quiet/noise). Differences between groups were tested first. Non-verbal intelligence, auditory attention scores, and verbal WM (digit span, total score) were entered as dependent variables in the analyses. Mann-Whitney U tests revealed that the two groups did not differ on the auditory attention measure ($U = 13.00$, $p = .290$) or the verbal WM measure ($U = 8.00$, $p = .080$). However, a statistically significant difference was found in nonverbal intelligence (CPM, $U = 5.50$, $p = .030$), with higher scores obtained by the NH children.

Subsequent Mann-Whitney U tests tested differences between the two groups in the forward and backward digit span performance in quiet and noise. These further analyses did not reveal statistically significant differences between NH and CI children in the forward digit span in quiet ($U = 11.50$, $p = .200$) or in noise ($U = 10.50$, $p = .160$), as well as in backward digit span in quiet ($U = 10.00$, $p = .140$) or in noise ($U = 18.00$, $p = .760$). Moreoer, the two groups did not differ on their fatigue scores ($U = 17.50$, $p = .72$).

Lastly, Wilcoxon signed-rank tests were run to test the effects of the experimental condition (quiet/noise) separately for each group (NH/CI users). The results did not show statistically significant differences in children's forward or backward digit span scores between conditions (quiet and noise, see also

Table 2). NH children performed equally well in quiet and noise both on the forward digit span, Z = .00, p = 1.00, and backward digit span, Z = -1.63, p = .10. Similar results were obtained for the CI group: Z = -.11, p = .91, for the forward digit span task, and Z = -.32, p = .75, for the backward digit span.

Following prior studies [12] we also computed a delta score, corresponding to the difference in children's performance between the quiet and noise condition. This was computed by subtracting children's digit span performance in noise to that in quiet. Spearman correlational analyses did not reveal any significant correlation between this score and the fatigue score in the NH group, but a statistically significant correlation between the digit backward delta score (e.g. the magnitude of the ISE effect in the backward condition) and the fatigue score in the CI group: $\rho = .72$, $p < .05$.

3.2 Psychophysiological measures: Pupil dilation

Due to a technical problem with the eye-tracking apparatus, pupil data were missed for all the five NH participants, who were assessed the same afternoon. We could thus run analyses only on the CI children's pupil data.

Data preparation. All pupil data have been pre-processed, removing artifacts like blinks and unrealistic pupil size values [35]. Moreover, to control for the high inter-individual variability in pupil size, corrected pupil dilations were computed [36] by subtracting the child's baseline pupil diameter from the pupil diameter recorded during the digit span tasks (corrected pupil dilation = on task pupil diameter– baseline pupil diameter). Corrected pupil dilation data were obtained for each digit span item in forward and backward condition. As a measure of children's maximum cognitive effort, we decided to consider only the time interval corresponding to the last correctly recalled digit string (i.e., maximum span) during the forward and backward digit span conditions.

Differences in pupil dilation between the quiet and noise digit span conditions were tested by Wilcoxon signed-rank tests. CI children's corrected pupil dilation on each task (forward digit span/backward digit span) and acoustic conditions (quiet/noise) were entered as dependent variables in these analyses. The results revealed no significant statistical differences in pupil dilation between conditions (quiet/noise) for the forward digit span task (Z = -.63, p =.528). However, in the backward digit span task the difference between the two acoustic conditions approached statistical significance (Z = -1.89, p =.058) (see Figure 1).

This latter result was further explored by a mass-univariate approach that tested the effects of the experimental condition on pupil dilation time series. The correction for multiple comparisons was achieved through cluster-based permutational methods. These statistical techniques have proven to be effective in detecting subtle differences across biological time series characterized by a massive number of time points [37]. The analysis was restricted to a time window of interest defined as 3 seconds after the last correctly remembered digit string. After selecting a-priori the time fragment of interest, the cluster-based permutation test highlighted a significant difference between the quiet and noise conditions ($p<0.05$ cluster corrected) in the backward digit span task.

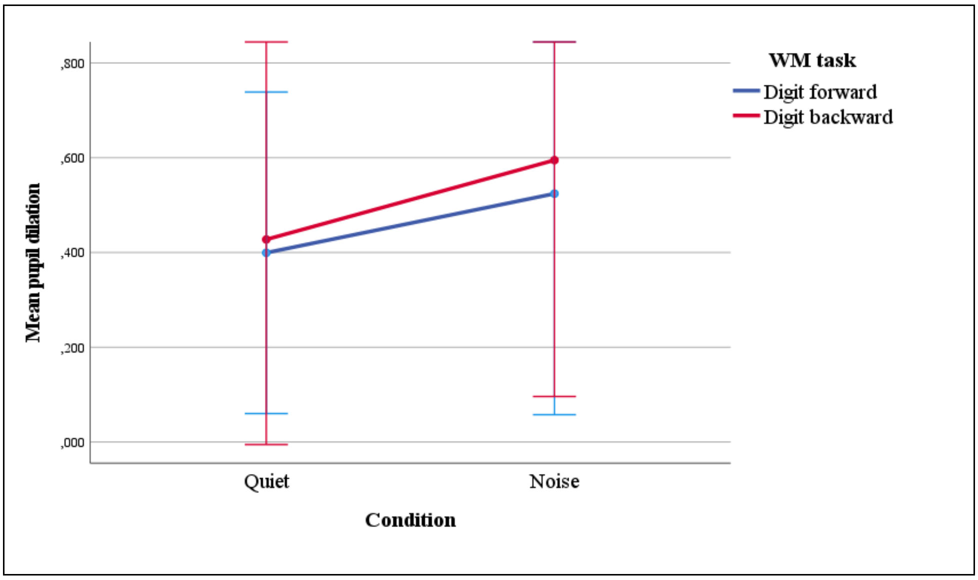

Figure 1 – CI children's pupil dilation in quiet and noise for the forward and backward digit span tasks.

4 Conclusions

This study moved from prior research [12] showing that in serial recall tasks individuals with better verbal WM abilities show greater ISE than individuals with poorer verbal WM. It has been speculated that high span individuals could be more vulnerable to the ISE because the irrelevant sounds interrupt their reshearsal processes. Low span individuals, who rely less on verbal rehearsal, would show lower susceptibility to the ISE. We tested this hypothesis by comparing the ISE on the verbal digit span performance of a group of CI users with congenital sensorineural HL and a control group of NH children. Numerous studies show that CI users suffer from a verbal WM deficit, which seems directly related to their less efficient or poorer use of verbal rehearsal (see [25]). Thus, in line with [12], these children should show a smaller ISE than NH children, who have more efficient rehearsal strategies and rely more on them.

The CI participants in this study were a highly selected and high performing group. Most had received an early auditory compensation and five were fitted with bilateral implants. None of them presented additional disabilities. Three of the CI users scored below age norms on the digit span task, and in general the digit span scores of this group were lower than those of their NH controls. However, the differences between the two groups were statistically non-significant.

Contrary to our expectations, the non-parametric analyses did not reveal differences between the WM performance (forward and backward) of the two groups, nor between the two performance conditions (quiet and noise). Both groups resulted to be little sensitive to the ISE. In line with Elliott and Cowan [12], a lack of significant ISE on children's performance could be explained by reduced reliance on verbal rehearsal strategies. However, this hypothesis seems unlikely as the participants in this study were sufficiently old to make significant use of subvocal rehearsal [19]. An alternative interpretation is that both groups were sufficiently able to exert cognitive control over their performance and thus were able to efficiently (re)allocate their mental resources, compensating well for the interference generated by the irrelevant speech signals [22, 23]. As noted earlier, the CI participants in this preliminary study represented a high-performing group. It is important to remind that the majority (five) of the CI children were fitted with bilateral implants. Others [38] have demonstrated that bilateral implant users are better than monolateral implant users at compensating for the interference of noise in speech perception tasks. Likely, this ability extends also to other cognitive tasks.

Other findings of this study suggest, however, that these children experienced a greater cognitive effort in noise than in quiet, and this was most apparent in the backward digit span task, i.e. the task involving the

greater executive control demands. The backward digit delta score (e.g., the difference between the backward digit span performance in quiet and noise) correlated significantly with children's self-reported fatigue. The analyses run on children's pupil dilation, a physiological marker of cognitive effort, corroborated this finding, revealing significant differences in CI children's corrected pupil dilation between the quiet and noise backward digit span conditions. These converging findings suggest the need to integrate behavioural measures with physiological measures of cognitive effort in studies exploring the ISE on cognitive performance. Psychophysiological measures may indeed appear more sensitive to children's perceived fatigue, which may not emerge when behavioural measures alone are considered.
The finding that ISE affected more the backward digit span than forward digit span performance was not expected nor was entirely consistent with prior studies that have documented ISE on verbal short-term memory or serial recall tasks [20, 21]. Our findings suggest that for high-performing CI users, the ISE emerges only when individuals have insufficient executive control to contrast it. This happens for instance when extra executive control resources have been already recruited for other cognitive/memory tasks (as in the backward digit span condition). Many learning situations in a classroom involve a large deployment of executive control resources [39]. In these situations, children can be most vulnerable to the ISE, with consequences not only for their performance but also for their perceived fatigue and general well-being [40].
These very preliminary findings suggest thus that for high-performing CI users the locus of the ISE is at the level of the central executive more than at the level of the phonological loop (or verbal rehearsal processes). At the moment, however, this hypothesis remains open, as the low number of participants in this study makes it difficult to draw any robust conclusion from these findings. To test this hypothesis further, we plan to extend the study to a larger sample of CI users, including monolateral CI users and children with lower verbal WM.

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