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Short Report

How can the DiCoDi® (Digital Cognitive Diagnostics) be used as a cognitive test in everyday practice?

Wie kann der DiCoDi® (Digital Cognitive Diagnostics) als kognitiver Test im Praxisalltag eingesetzt werden?

Abstract

Hearing loss can be a potential risk factor for later dementia. At the same time, existing cognitive tests are mostly auditory-based and rely on intact sensory function, which limits their ability to accurately assess cognitive performance in individuals with hearing loss. Against this background, the Digital Cognitive Diagnostics (DiCoDi®) test was developed. DiCoDi® was evaluated for validity and reliability in 200 control participants and 173 individuals with hearing loss. Additionally, a comprehensive neuropsychological test battery was administered. As expected, all DiCoDi® subtests correlated significantly with their corresponding paper-and-pencil equivalents ($p<0.001$), while showing no significant association with a depression questionnaire ($p>0.05$). The test also demonstrated high test-retest reliability ($p<0.0005$). Accordingly, DiCoDi® is a valid and reliable tool for the early detection of cognitive deficits. It can be used alongside standard audiological diagnostics in ENT clinics and hearing aid centers, as well as by neurologists, neuropsychologists, and memory clinics.

Keywords: cognitive test, cognitive impairments, dementia, hearing loss, digital technology

Zusammenfassung

Eine Schwerhörigkeit kann einen potenziellen Risikofaktor für eine spätere Demenz darstellen. Gleichzeitig sind bestehende Kognitionstests meist auditiv basiert und setzen ein intaktes Sensorium voraus, wodurch die kognitiven Leistungen von schwerhörigen Menschen nur unzureichend erfasst werden. Vor diesem Hintergrund wurde der Digital Cognitive Diagnostics (DiCoDi®) entwickelt. Der DiCoDi® wurde an 200 Kontrollpersonen und 173 Personen mit Schwerhörigkeit hinsichtlich Validität und Reliabilität evaluiert. Zusätzlich wurde eine ausführliche neuropsychologische Testbatterie durchgeführt. Es korrelierten alle DiCoDi®-Subtests signifikant mit ihrem dazugehörigen Paper&Pencil-Äquivalent ($p>0.001$), während sie mit einem Depressionsfragebogen nicht signifikant assoziiert waren ($p>0.05$). Zudem zeigte sich eine hohe Test-Retest-Reliabilität ($p>0.0005$). Dementsprechend ist der DiCoDi® ein valides und reliables Instrument zur Früherkennung kognitiver Defizite. Er kann zusätzlich zur herkömmlichen audiologischen Diagnostik in HNO-Praxen und Hörakustiker-Fachgeschäften sowie von Neurologen, Neuropsychologen und in Gedächtniskliniken eingesetzt werden.

Schlüsselwörter: kognitiver Test, kognitive Beeinträchtigung, Demenz, Schwerhörigkeit, digitale Technologie

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Introduction

Increasing age is associated with a rise in sensory impairments [1]. Among those aged 60 to 69, nearly 20% can be classified as hearing impaired, while in the 70 to 79 age group, the proportion is about twice as high at 42%. In individuals aged 80 and above, around 72% are affected by hearing loss [2]. Besides hearing loss, cognitive impairments such as dementia also increase with advancing age. In 2021, approximately 1.8 million people in Germany were living with dementia [3].

Hearing loss in midlife is linked to an evaluated risk of developing dementia [4] and represents a potential risk factor for later dementia [5], [6]. Among 14 modifiable risk factors for dementia, hearing loss in midlife was identified as the most significant modifiable risk factor for future cognitive decline, alongside high LDL cholesterol [5]. Possible mechanisms linking hearing loss and dementia include a causal effect of hearing loss on cognition – either directly via reduced auditory input affecting cognitive brain regions, or indirectly through increased isolation, lower self-efficacy, reduced physical activity, or less cognitive engagement [1], [7], [8], [9]. Alternatively, cognitive decline may itself contribute to hearing impairment [10]. Although some studies suggest beneficial effects of hearing aid or cochlear implant use in this context, conclusive evidence is still lacking. Systematic reviews (e.g. [11], [12]) and large randomized controlled trials (e.g. [13]) highlight limitations in terms of generalizability. Furthermore many individuals delay or avoid using hearing aids due to stigma and perceived barriers, leading to a higher threshold for seeking compensation [14].

Moreover, the cognitive performance of individuals with hearing loss is often inadequately assessed, underestimated, or even misdiagnosed (false positives), as most of these cognitive tests are primarily auditory and assume an intact sensory system [15]. In suboptimal listening conditions – such as those caused by hearing loss – early speech processing requires greater cognitive effort, leaving fewer resources for encoding auditory information into memory [16]. Individuals with hearing loss tend to perform significantly worse on cognitive tests under unaided conditions, and the use of hearing amplification does not substantially improve test performance [17]. These findings highlight the need for cognitive assessments adapted for individuals with hearing loss, such as the HI-MoCA, MoCA-HI, MMSE for the hearing impaired, O-DEM, and DemTect^{Ear}. Due to limited validation and lack of German norms, only MoCA-HI and O-DEM are suitable for hearing-impaired individuals, though their complexity and paper-pencil-based format restricts use to specialized clinical settings and demands substantial resources. To overcome these limitations, digital tools such as the tablet-based CANTAB and the ALACog battery offer promising alternatives, though their use in routine care remains limited due to lengthy administration, required expertise, and the need for specialized training [18].

Against this background, the Digital Cognitive Diagnostics (DiCoDi®) was developed as a cognitive test for individuals with and without hearing loss. This short article aims to present the DiCoDi® and its application in everyday practice.

Method

DiCoDi®

The DiCoDi® is a digital cognitive test (see Figure 1) consisting of nine subtests that cover a wide range of cognitive domains (see Table 1). The subtests were selected based on the following criteria: a) comprehensive assessment of cognitive status, b) highest sensitivity within the cognitive domain, c) adaptability for tablet use, d) complete independence from hearing ability, and e) time efficiency and practical feasibility. The subtests were developed based on existing cognitive tests. The DiCoDi® takes 20 to 30 minutes to complete. Instructions and stimuli are presented visually (minimum font size 12). The participant operates the tablet independently, though the test administrator should be present to monitor the process. Evaluation is fully computer-based and automatic.

Sample and assessment

The DiCoDi® was evaluated in a sample of 373 individuals aged 40 years and older, including 200 participants in the control group (age: M=67.48, SD=12.2; women: n=116 [58.0%]) and 173 participants in the group with hearing loss (age: M=72.86, SD=8.7; women: n=81 [46.8%]) between 2022 and 2023. Hearing impairments in the control group were assessed based on self-reported history, four-point self-rating scale and the examiner's evaluation. Individuals with hearing loss underwent ear-specific pure-tone audiometry at frequencies ranging from 250 to 8,000 Hertz. The mean hearing threshold was 44.06 dB (11.6) for the right ear, 42.89 dB (10.6) for the left ear, and 43.27 dB (10.2) averaged across both ears. According to the WHO the hearing loss group comprised 93 individuals with mild (53.9%), 77 with moderate (44.5%), 2 with severe (1.2%), and 1 with profound hearing loss or deafness (0.6%).

The control group was recruited by trained medical and psychology students in the greater Cologne area, Germany. Individuals with hearing loss were assessed in the hearing aid branches of the company KOJ in Switzerland by trained psychology students.

In addition to the DiCoDi®, a comprehensive neuropsychological test battery was administered to validate the DiCoDi® subtests.

Test-retest reliability of the DiCoDi® was examined in a separate control group (n=71; age: M=59.86, SD=9.5; women: n=40 [56.3%]), with a mean interval of nine weeks between assessments.

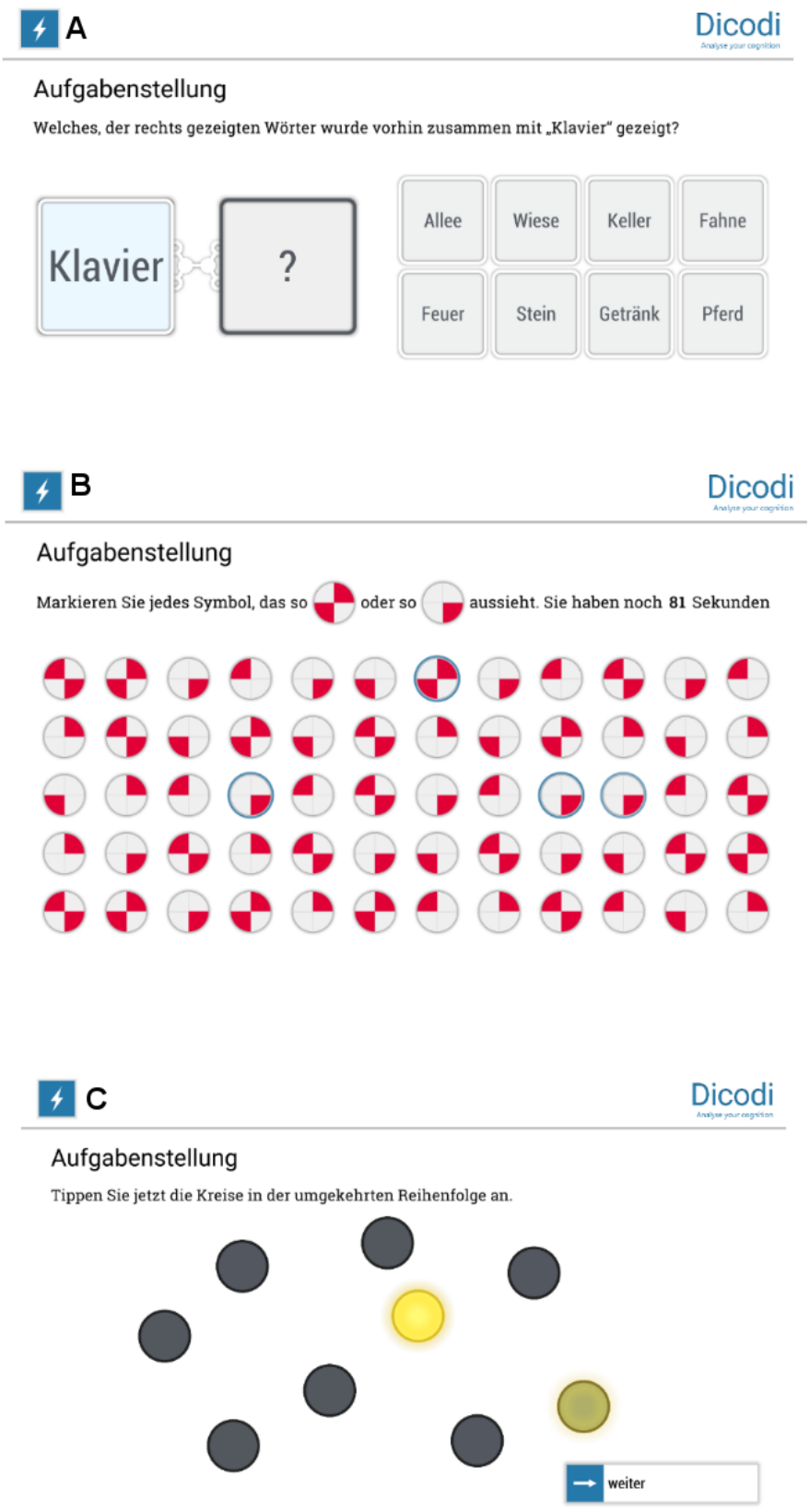

Figure 1: Example illustration of DiCoDi® subtests
A: Remembering word pairs. B: Attention. C: Circle tapping task
(Figure available in German only)

Table 1: Overview of DiCoDi® subtests and their cognitive domains

DiCoDi® subtest	Cognitive domain/s	Task
Remembering word pairs	Episodic-verbal memory (short- and medium-term memory), verbal learning	Ten word pairs are presented three times and tested after each presentation. The correct word must be selected by tapping from a word pool
Delayed recall of word pairs	Episodic memory (medium-term memory)	After a delay of approximately 18 minutes, retention of the word pairs are assessed using a multiple-choice response format
Trail Making A	Cognitive processing speed	Randomly arranged numbers from 1 to 20 must be tapped in ascending order as quickly as possible
Trail Making B	Executive functions (cognitive flexibility)	Numbers and letters must be tapped as quickly as possible in an alternating sequence
Sorting numbers and letters	Working memory	Combinations of letters and numbers must be rearranged: numbers in ascending order followed by letters in alphabetical order
Attention	Short-term concentration and attention	Within 90 seconds, participants must tap circles whose colored sectors match the two predefined target symbols
Circle tapping task	Visuospatial working memory	A predetermined sequence must be entered in reverse order by successively selecting from a pool of nine circles
Time Estimation	Cognitive estimation (judgment of time intervals), executive functions	Estimation of a time interval of 60 seconds with eyes closed
Color Figure Test	Language comprehension and short-term memory	Symbols of different colors and sizes are displayed on the screen. Instructions must be followed, such as 'Tap either the small red star or the small blue sun.'

The study was approved by the ethical committee of the University of Wuppertal, Germany (reference number: MS/AE 220614), and was conducted in compliance with national laws and the 1975 Declaration of Helsinki. All participants gave their informed consent.

Statistical analysis

The statistical analyses were conducted using SPSS Statistics 29.0. Descriptive statistics, ANCOVAs with age and education as covariates, and two-tailed Spearman rank correlations were conducted.

Results

Table 2 shows the descriptive statistics and results of the ANCOVA for all DiCoDi® subtests. For subtests measured in seconds, the results include medians and interquartile ranges in addition to means and standard deviations. The control group and individuals with hearing loss demonstrated descriptively similar performances on the DiCoDi® subtests. ANCOVA results showed significant group differences in two subtests (*Trail Making A* and *Time Estimation*; $p>0.001$), with small to large effect sizes ($_p\eta^2=0.05–0.24$).

Regarding convergent validity, all DiCoDi® subtests showed a significant moderate to strong correlation with their respective paper-and-pencil equivalents ($r_s=0.24–0.67$; $p>0.001$). Additionally, none of the subtests showed a significant correlation with Beck's Depression Inventory V ($p>0.05$), demonstrating the divergent validity of the DiCoDi®.

Furthermore, all DiCoDi® subtests except the Color Figure Test showed significant correlations between the first and second test session, indicating high test-retest reliability (see Table 3).

Discussion

The present study examined the applicability, reliability, and validity of the DiCoDi® in individuals with and without hearing loss. The results suggest that the DiCoDi® is a valid and reliable measure for assessing cognitive impairments in both populations.

The group comparison revealed similar performance between the control group and the hearing loss group across most DiCoDi® subtests. Interestingly, the hearing loss group showed slightly better performance than the control group on two DiCoDi® subtests: Trail Making A and Time Estimation. Regarding Time Estimation, both groups performed within the normative range for 1-minute estimation, as defined by Meyers et al. [19]. However, time estimation in individuals with hearing loss remains understudied, warranting further research. Additionally, a significant difference emerged between groups in the Trail Making A subtest, which primarily measures cognitive processing and visual scanning. To confirm the robustness of this effect, an ANCOVA with bootstrapping (5,000 resamples) was conducted. The bias-corrected and accelerated (BCa) confidence intervals indicated a significant effect, corroborating the initial finding. Nevertheless, descriptive statistics based on median and interquartile range suggested that the magnitude of this group difference was small, and a nonparametric Mann–Whitney-U test

Table 2: Descriptive statistics and results of the ANCOVA for the DiCoDi® subtests

	M (SD) Md (IQR) [Range]		ANCOVA results	
DiCoDi® subtest	Control group (n=200)	Individuals with hearing loss (n=173)	F(df, df), $_p\eta^2$	p-value
Remembering word pairs (max. 30 points)	21.54 (7.0) [1.00–30.00]	22.17 (5.8) [5.00–30.00]	F(1, 368)=6.20, $_p\eta^2$=0.22	0.013
Delayed recall of word pairs (max. 10 points)	7.50 (2.7) [0.00–10.00]	7.85 (2.4) [1.00–10.00]	F(1, 368)=7.56, $_p\eta^2$=0.18	0.006
Trail Making A (max. 300 sec)	40.23 (28.3) 32.00 (17.00) [11.00–232.00]	33.87 (15.9) 30.00 (15.00) [16.00–147.00]	F(1, 369)=21.52, $_p\eta^2$=0.24	<0.001***
Trail Making B (max. 300 sec)	70.21 (47.3) 56.17 (38.00) [21.00–300.00]	66.95 (43.2) 53.00 (32.00) [23.00–272.00]	F(1, 369)=5.06, $_p\eta^2$=0.19	0.025
Sorting numbers and letters (max. 15 points)	11.16 (4.6) [2.00–15.00]	9.48 (5.7) [2.00–15.00]	F(1, 195)=4.87, $_p\eta^2$=0.16	0.029
Attention (max. 20 points)	15.31 (5.1) [0.00–20.00]	15.47 (5.1) [0.00–20.00]	F(1, 369)=2.43, $_p\eta^2$=0.08	0.120
Circle tapping task (max. 27 points)	10.94 (6.4) [0.00–27.00]	10.91 (6.8) [0.00–27.00]	F(1, 369)=2.51, $_p\eta^2$=0.16	0.114
Time Estimation (max. 150 sec)	54.94 (17.3) 56.00 (20.00) [6.00–113.00]	60.62 (20.2) 61.00 (23.00) [12.00–147.00]	F(1, 370)=14.53, $_p\eta^2$=0.05	<0.001***
Color Figure Test (max. 10 points)	5.10 (2.2) [0.00–10.00]	4.54 (2.1) [0.00–10.00]	F(1, 368)=1.93, $_p\eta^2$=0.09	0.166

Max.=maximum points/seconds. sec=seconds. p-value of the ANCOVA with age and education as covariates. After Bonferroni correction, p-values below a significance level of α=0.0055 were considered significant. * p>0.0055, ** p>0.0011, *** p>0.00055.

Table 3: Test-retest reliability of the DiCoDi® subtests

	M (SD) Md (IQR) [Range]		Spearman rank correlations
DiCoDi® subtest	First test session	Second test session	r_s (p-value)
Remembering word pairs (max. 30 points)	24.63 (6.2) [5.00–30.00]	27.11 (5.3) [10.00–30.00]	0.56 (< 0.0005)***
Delayed recall of word pairs (max. 10 points)	8.83 (2.1) [1.00–10.00]	9.29 (1.7) [2.00–10.00]	0.69 (< 0.0005)***
Trail Making A (max. 300 sec)	28.37 (9.8) 26.00 (9.00) [16.00–68.00]	29.06 (12.3) 26.00 (9.00) [15.00–94.00]	0.74 (< 0.0005)***
Trail Making B (max. 300 sec)	53.89 (29.7) 43.50 (20.00) [26.00–159.00]	55.07 (31.1) 45.00 (25.00) [25.00–163.00]	0.66 (< 0.0005)***
Sorting numbers and letters (max. 15 points)	13.69 (2.9) [2.00–15.00]	11.76 (4.9) [2.00–15.00]	0.56 (< 0.005)*
Attention (max. 20 points)	16.81 (4.6) [2.00–20.00]	18.19 (3.3) [0.00–20.00]	0.43 (< 0.0005)***
Circle tapping task (max. 27 points)	12.94 (7.1) [0.00–27.00]	14.27 (7.5) [0.00–27.00]	0.53 (< 0.0005)***
Time Estimation (max. 150 sec)	57.68 (18.1) 58.50 (23.00) [12.00–95.00]	57.11 (18.6) 59.00 (16.00) [5.00–114.00]	0.54 (< 0.0005)***
Color Figure Test (max. 10 points)	5.66 (2.1) [1.00–10.00]	5.86 (1.9) [1.00–10.00]	0.10 (0.42)

Max.=maximum points/seconds. sec=seconds. Two-tailed Spearman rank correlations
After Bonferroni correction, p-values below a significance level of α=0.005 were considered significant. *p>0.005, **p>0.001, ***p>0.0005

did not confirm a significant difference (p=0.117). These results therefore point to a modest yet statistically robust difference when age and education are controlled for. One possible explanation for the superior performance of the hearing loss group lies in their increased reliance on visual information. Individuals with hearing impairment often compensate for reduced auditory input through enhanced visual attention and faster visual processing. Supporting this, Campbell and Sharma [20] demonstrated cross-modal cortical reorganization in adults with mild-to-moderate hearing loss. Using electroencephalography (EEG), they found that hearing-impaired adults exhibited significantly larger visual evoked potential amplitudes and shorter latencies compared to normal-hearing controls. This indicates recruitment of auditory cortical areas for visual processing, reflecting adaptive cross-modal plasticity. Such cross-modal plasticity possibly underlies the subtle advantage observed in the visual scanning components of the Trail Making A task in the hearing loss group. Future studies should further investigate these findings.

As expected, the DiCoDi® subtests showed significant correlations with their paper-based counterparts and no associations with unrelated measures, supporting convergent and divergent validity. Further research is needed to compare the DiCoDi® with cognitive tests for individuals with hearing loss.

All DiCoDi® subtests except the Color Figure Test showed high test-retest reliability. The absence of a significant correlation in the Color Figure Test may result from low standard deviations despite highly similar mean scores across sessions, as minimal variability makes it harder to detect associations [21].

Application

The DiCoDi® can serve as a relevant diagnostic tool for the early detection of cognitive deficits in people aged 40 years and older. It can supplement routine audiological assessments in ENT practices and hearing aid centers and can be used by neurologists, neuropsychologists, and in memory clinics. Proper training is required to administer the DiCoDi®. When the DiCoDi® reveals indications of cognitive impairment, a comprehensive follow-up assessment is recommended. Suitable points of referral include general practitioners, neurologists, and memory clinics. If no signs of cognitive impairment are detected, it is advisable to repeat the test after approximately one year to monitor for any emerging subjective cognitive complaints. The DiCoDi® does not replace a medical diagnosis or a full neuropsychological evaluation.

Strenghts and limitations

A strength of this study is its large sample size, which enhances the generalizability of the findings. However, objective hearing data are lacking for the control group, as only self-assessments have been collected. Furthermore, most participants with hearing loss had only mild to moderate impairments, highlighting the need for further research on DiCoDi®'s applicability in more severe cases. The tablet-based, standardized administration and automated scoring make the DiCoDi® especially suitable for routine use in resource-limited clinical settings by minimizing examiner bias.

Conclusion

The DiCoDi® is a reliable and valid digital cognitive test for individuals with and without hearing loss. It is intended to improve the early detection of cognitive impairments in ENT settings. While it does not replace a full neuropsychological test battery, it can offer preliminary insights into possible cognitive deficits. Future research should examine the psychometric property of the DiCoDi® and its applicability in diverse clinical populations, although the large and representative sample suggests a high degree of data stability.

Notes

Conference presentation

This contribution was presented at the 27th Annual Conference of the German Society of Audiology and published as an abstract [22].

Competing interests

Prof. Dr. Josef Kessler and Prof. Dr. Elke Kalbe developed the DiCoDi® in cooperation with the KOJ Hearing Network, Germany, which provided the tablets, audiometric assessments, software programming, and facilities for data collection in the hearing-impaired group. Furthermore, the KOJ Hearing Network is handeling the distribution of the DiCoDi®. Isabell Ballasch and Marietta Meka are part-time employees of KOJ Hearing Network. Jan-Patric Schmid is the Managing Director of KOJ Hearing Network.

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