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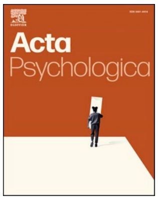

The potential transfer effect of musical expertise to auditory verbal working memory: Does native language matter?

Peixin Nie[a,b,c,*], Barbara Tillmann[d,e], Vesa Putkinen[b,f,g], Caitlin Dawson[a,b,c], Sha Tao[h,i], Mari Tervaniemi[a,b,c]

[a] *Faculty of Educational Sciences, Department of Education, University of Helsinki, Helsinki, Finland*
[b] *Cognitive Brain Research Unit, Faculty of Medicine, University of Helsinki, Helsinki, Finland*
[c] *Centre of Excellence in Music, Mind, Body and Brain (MMBB), Faculty of Medicine, University of Helsinki, Finland*
[d] *Lyon Neuroscience Research Center, CRNL, CNRS, UMR 5292, INSERM U1028, F-69000, Lyon, France*
[e] *Université Bourgogne Europe, CNRS, LEAD UMR5022, 21000, Dijon, France*
[f] *Turku PET Centre, University of Turku, Turku, Finland*
[g] *Turku University Hospital, Turku, Finland*
[h] *State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, 100875, China*
[i] *IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, 100875, China*

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ABSTRACT

Musical expertise has been shown to facilitate verbal working memory (WM) performance, but the findings lacked consistency. Given the overlapped auditory encoding process for language and music, there may be an association between one's native language background and the effects of musical expertise. In the present study, we investigate (1) the effects of musical expertise on verbal WM with different native language backgrounds and (2) the role of tone memory in the music-verbal WM link as a potential mechanism behind it. The data were collected as part of an experimenter-monitored online project, in which various memory functions were measured in musicians and nonmusicians speaking either tonal language (Mandarin Chinese) or nontonal language (Finnish). Results showed advantages of musical expertise on verbal WM only in the Finnish participants, but not in the Chinese participants. Tone sequence memory was identified as a mediator in the relationships between musical expertise and verbal WM. Our finding suggests that the beneficial effects of musical expertise on verbal WM could differ between different native language backgrounds. This potential benefit may come through the enhanced encoding of the auditory tone stimuli, which was shown to be possibly affected by language backgrounds. Therefore, we highlight the importance of considering language background in future studies when investigating the potential benefits of musical expertise and music interventions.

1. Introduction

The potential beneficial effects of musical experience on working memory (WM) functions have been studied extensively over the past decades, yet a consensus has not been reached. Studies have reported evidence that musicians outperform nonmusicians on various aspects of memory, such as memory of tonal materials (Ding et al., 2018; Pallesen et al., 2010), verbal materials (Franklin et al., 2008; Saarikivi et al., 2019), and materials in other modalities (Bialystok & DePape, 2009; Suárez et al., 2016) in both cross-sectional studies and longitudinal studies (Guo et al., 2018; Roden et al., 2014), see Talamini et al., 2017 for a meta-analysis. Recent studies found that brief music listening could also facilitate the visuospatial sketchpad and central executive component of WM (Giannouli et al., 2019, 2024). However, inconsistent findings have also been reported. For example, studies showed that musically trained participants who speak Danish and Finnish showed advanced WM maintenance compared to participants without musical training (Hansen et al., 2013; Saarikivi et al., 2019), yet no differences were found in WM manipulation. However, the positive effects of musical training have been found on WM manipulation, but not on WM maintenance in Chinese-speaking and Japanese-speaking children (Guo et al., 2018). These varying results across participants from different language groups suggest that language background of the participants could be one influential factor, as proposed by Nie et al. (2022). It is thus

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* Corresponding author at: P.O. Box 21, FI-00014, University of Helsinki, Finland.
E-mail address: Peixin.nie@helsinki.fi (P. Nie).

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necessary to conduct comparative studies with the same setting in different native language groups.

Music and language share similarities as they both heavily rely on acoustic features to convey meanings and information, e.g., pitch and rhythm for music, intonation and accentuation patterns for speech. Previous research found overlapped brain activation for these processes (see Patel, 2012; Peretz et al., 2015). These led to potential bidirectional transfer effects from the learning in one domain to the perception and cognition in the other domain. For the music-to-language transfer, musical training has been found to be associated with enhanced language/speech-related performance, i.e., speech-in-noise performance (Parbery-Clark et al., 2009; Slater et al., 2015), phonological awareness (Degé & Schwarzer, 2011; Linnavalli et al., 2018), reading (Flaugnacco et al., 2015) and neural encoding of speech sounds (Tierney et al., 2013). For the language-to-music transfer, language experience as a native speaker could benefit music perception. For example, Finnish speakers showed enhanced pre-attentive processing of duration changes in musical sounds in comparison to German and French speakers (Marie et al., 2012; Tervaniemi et al., 2006), as the quantity nature of the Finnish language in which duration contrasts can signal different meanings.

In contrast to Finnish, which is a quantity language that uses phonemic duration to convey semantic meaning, some other languages, such as Mandarin Chinese, Cantonese, and Vietnamese, extensively rely on variations in lexical tones to convey different meanings. For example, in Mandarin Chinese, the one word "ma" can have four different tones that lead to distinct meanings: mā means mother; má means hemp; mǎ means horse; and mà means scold. Speaking a tonal language has been reported to be beneficial for musical melodic processing in multiple studies (Bidelman et al., 2013; Liu et al., 2023; Pfordresher & Brown, 2009). Nie et al. (2024) investigated the higher-order cognition of tone sequences, namely the tone WM, in Chinese and Finnish speakers, comparing musicians and non-musicians. The results showed that the Chinese participants exhibited more advanced WM maintenance for tone sequences, compared with Finnish participants, regardless of musical expertise or tonal structure of the musical materials.

Native language background may modulate the cognitive benefits of musical training, particularly in verbal working memory. In addition, memory for musical tone sequences can be affected by both musical expertise and native language background (Bidelman et al., 2013; Nie et al., 2024). We propose that the following mechanisms underlie the potential benefits of musical training on verbal working memory: (1) Musical expertise benefits memory for pitch and melodies because of the prolonged and intensive training in musical sound processing. This creates a bridge between musical expertise and tone sequence memory. (2) Tone sequence memory and verbal WM are linked, as suggested by Baddeley and Hitch's (1974) multicomponent WM model regarding the role of the phonological loop. Supporting this link, their later work (Williamson et al., 2010) further revealed phonological similarity effects in letter recall and tonal similarity (as the musical equivalent of phonological similarity) effects in pitch serial recall. They proposed that the processing of musical and verbal sounds may overlap in short-term memory and suggested that pitch sound processing may be incorporated in the WM model. (3) Speaking tonal languages can also be beneficial for pitch/tone memory (Bidelman et al., 2013; Nie et al., 2024). Therefore, both language and music-related experience may influence memory for the pitch/tone stimuli and, possibly, also for verbal stimuli as a result. Based on these points, we hypothesize that music expertise could benefit tone sequence memory as well as verbal memory, notably by facilitating the phonological loop in the verbal WM process. Further, the effects from language domains may interact and lead to inconsistent transfer effects of music expertise in different language contexts.

In the present study, we aim to compare musicians and nonmusicians who speak Mandarin Chinese, a tonal language, or who speak Finnish, a non-tonal language. The performance of the tone memory task will be used as an indicator of short-term memory for tone sequences. The Digit Span (DS) with forward and backward tasks was used as an indicator of WM maintenance and WM manipulation for verbal stimuli, respectively. We focus on the effects of musical expertise on verbal WM and whether this effect could differ between different language backgrounds. How short-term memory for tone sequences might contribute to the music-verbal WM transfer will be examined to illustrate a potential underlying mechanism. We expected to see different results regarding the effects of musical expertise on verbal WM between Mandarin and Finnish speakers and hypothesized that the tone sequence memory may play a role in the transfer effect of music expertise on verbal WM.

2. Method

2.1. Participants

Twenty-two Finnish-speaking musicians, 23 Finnish-speaking nonmusicians, 22 Mandarin Chinese-speaking musicians, and 24 Mandarin Chinese nonmusicians participated in the experiment via an online platform. Due to the challenges in recruiting participants during the COVID-19 pandemic, participants were recruited using convenience sampling via social media and email lists, without a priori power analysis to determine the sample size. All musicians had at least five years of professional music training and worked as musicians or were currently studying music at a professional level. All instruments that the musicians practiced for more than five years are listed in Supplementary Table 1. All nonmusicians had less than five years of musical training outside their regular school curriculum. All participants reported intact hearing and no medication in their central nervous system. One Finnish nonmusician participant was excluded from data analysis due to prior Mandarin Chinese learning. The remaining participants had no experience learning the native language of the other language group. To balance the age between Finnish and Chinese groups, one Finnish musician and one Finnish nonmusician were excluded. Due to technical problems, one Finnish musician, two Finnish nonmusicians, three Chinese musicians, and one Chinese nonmusician could not complete the tone memory forward task. Therefore, the final sample included in the statistical analysis consists of 20 Finnish musicians (average age, 29.70 years; 15 females), 19 Finnish nonmusicians (average age, 26.84 years; 17 females), 19 Chinese musicians (average age, 27.63 years; 13 females), and 23 Chinese nonmusicians (average age, 25.96 years; 15 females). The years of music training in each group are shown in Fig. 1.

2.2. Measurements

2.2.1. Background information questionnaire

The background data were collected using a Qualtrics platform (https://www.qualtrics.com/). It consisted of demographic information (such as age, gender, and education level), a language history questionnaire, a music experience questionnaire, and two questions about dancing and visual arts activities. The education level ranges from 1 to 7 (1 = high school or equivalent; 2 = pursuing bachelor's degree; 3 = Bachelor's degree; 4 = pursuing master's degree; 5 = master's degree; 6 = pursuing doctoral degree; 7 = doctoral degree). The language history questionnaire dealt with the participants' native and second languages. The music questionnaire involved various questions about music experiences during childhood, music activities they were engaged in at present, and how they liked music. Detailed background information on the participants can be found in Table 1.

2.2.2. Digit Span (DS) tests (WAIS-III)

To measure the maintenance and manipulation in verbal working memory, the DS tests (with forward and backward subtests) were employed. They were derived from the Chinese and Finnish revised versions of the Wechsler Adult Intelligence Scale (WAIS) for Chinese- and Finnish-speaking participants, respectively (Gong, 1992; Wechsler

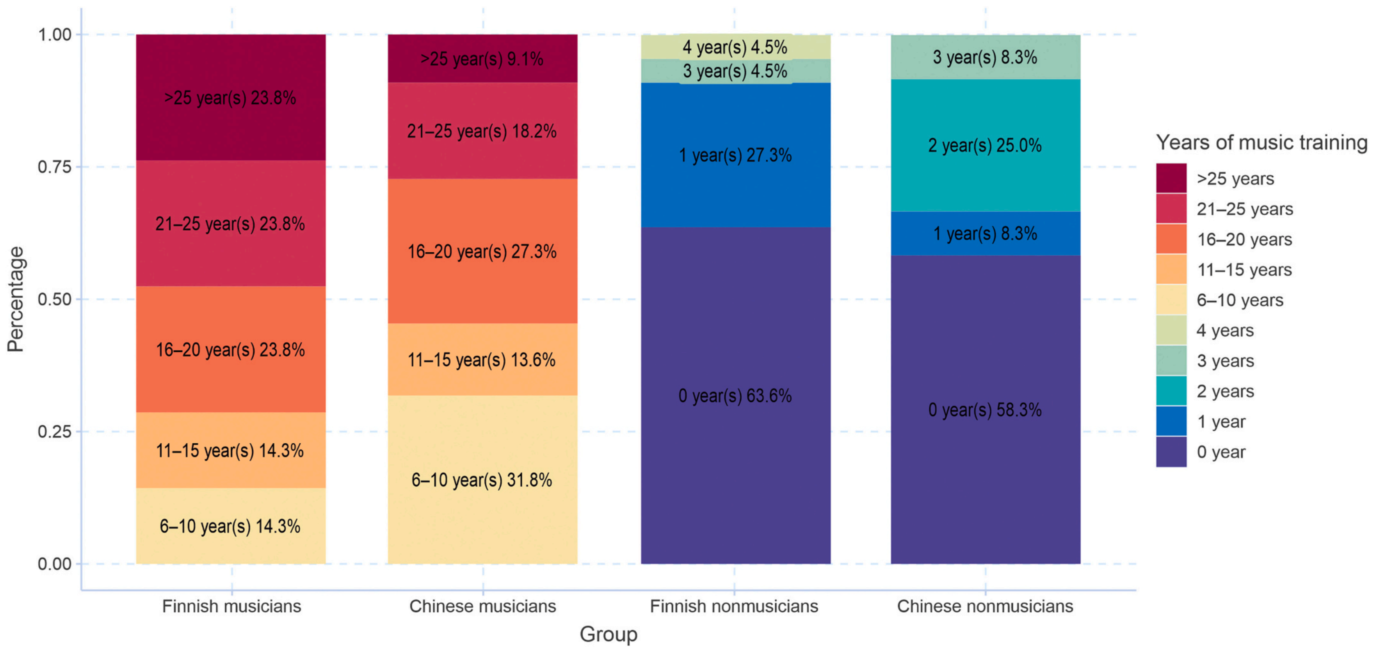

Fig. 1. The years of musical training of Finnish musicians, Chinese musicians, Finnish nonmusicians, and Chinese nonmusicians, respectively, and the proportion of training years in each group.

Table 1
Demographic information of participants.

Variables	Finnish Musicians	Finnish Nonmusicians	Chinese Musicians	Chinese Nonmusicians
N	20	19	19	23
Age	29.70 ± 4.50	26.84 ± 4.43	27.63 ± 4.44	25.96 ± 2.95
Gender (*N* of female)	15	17	13	15
Education level	3.70 ± 1.26	3.37 ± 1.12	4.26 ± 1.24	4.22 ± 1.20
Years of music training	19.55 ± 6.68	0.58 ± 1.12	17.11 ± 6.06	0.78 ± 1.09
Current music listening (hrs/week)	11.08 ± 9.11	6.13 ± 4.83	10.55 ± 7.12	10.63 ± 10.73
Number of learnt 2nd language[a]	3.45 ± 1.05	3.53 ± 0.77	1.68 ± 0.95	1.17 ± 0.39

[a] There is a notable difference in the number of foreign languages learned between participants from China and Finland. This can be attributed to the emphasis on communication skills within Finnish education. According to the Finnish school curriculum, all students receive weekly instruction in at least one foreign language, typically English, as well as Swedish, which is one of the official languages of Finland besides Finnish. These language lessons currently begin in primary school before the age of 12, previously before the age of 13. Additionally, many students choose to study German, French, Spanish, or various combinations of these languages during junior and senior high school. However, in the Chinese basic education system, English language is usually the only foreign language provided by the schools.

and Psykologien Kustannus Oy, 2005). In the forward task, participants heard a sequence of numbers and were asked to repeat all numbers correctly in the same order. In the backward span task, participants also heard several series of numbers, but were asked to recall all numbers correctly in reverse order. In both tasks, the sequences start with two digits, e.g., 2–4. Each block contained two trials of the same sequence length. Successive trials became one item longer until participants failed to recall both trials in one block or until the end of the list. The longest sequences at the end of the list consist of 12 digits. The total numbers of correctly recalled trials were marked as the final scores, separately for DS forward and DS backward task. Digit sequences were presented by previously recorded videos showing a research assistant reading the sequences aloud, with the same speed of one digit per second in both languages. The videos were presented by the PsychoPy Builder (Peirce et al., 2019) via the "share screen" function in Zoom.

2.2.3. *Tone sequence memory task*

In this task, pairs of tone sequences separated by a 3-s silent delay were presented and participants were required to indicate whether the second sequences were the same or different. The lengths of the tone sequences varied from five to seven tones. The tone sequences were constructed according to the sequences used in Schulze et al.'s (2012) study, half of which were melodies with tonal structures and half were melodies without tonal structures. For different pairs, two nonadjacent tones were exchanged so that the melodic contour was preserved (e.g., C A F E G – C A G E F). The first tone of the second sequence was never changed. For an example trial, see https://osf.io/mr3yp/files/osfstorage?view_only=abe12268f29c4782a09b9eca1649ffd8. The task consisted of 96 pairs of tone sequences in total, which were presented in four experimental blocks of 24 pairs each. The tonal/atonal pairs and same/different pairs were mixed in each block and the type of pair (same/different) changed after at most three trials (i.e., no more than three consecutive "same" or "different" trials). The same tone sequence was not presented consecutively as a same and a different pair. The participants were instructed that the sequence length would range from five to seven but would not be alerted when the length changed during the tasks.

Scores of the tone memory tasks were analyzed in the framework of signal detection theory. The discrimination sensitivity d' and the response bias c were calculated with *hits* (hits = $n_{\text{correctly answered different}}/n_{\text{all different pairs}}$) and *false alarms* (false alarm = $n_{\text{false answered different}}/n_{\text{all non-different pairs}}$), across all sequence length conditions and with both tonal and atonal structures. A higher d' indicates better discrimination performance. Positive values of bias c indicated that participants were more prone to answer "same". Only the scores of the tone memory forward task were reported here, indicating the maintenance of the tone material, which we hypothesized to be affected by language background and be influential to verbal WM. The experiments were programmed with PsychoPy Builder (Peirce et al., 2019), and run as a PsychoJS experiment on Pavlovia (http://pavlovia.org/).

2.3. Procedures

The entire experiment was conducted online, but under the control of the experimenter. After enrollment in an online booking system, participants were invited to join a Zoom link (in Finland) or a Voov link (in China) at the scheduled time and start the one-to-one experiment with the experimenter via a video camera. The participants then either received a link to the task or were shared with the experimenter's screen, presenting the task material. For the DS task, participants were instructed to watch a prerecorded video that introduced the instructions and the digit sequences and then repeat the sequence out loud. The experimenter controlled in the background whether the test should be continued or not according to the participant's responses and marked the scores on a paper sheet. The answers of the participants were video recorded with permission from the participants to double-check the scores. For the tone memory task, participants received the links to the tasks on the website (pavlovia.org) and completed the tasks while sharing the screen with the experimenter. Participants' responses were recorded automatically on the Pavlovia platform.

According to organizational procedures, a statement of the ethics will be requested from the University of Helsinki Ethical Review Board in the Humanities and Social and Behavioral Sciences if a study meets certain requirements as specified by the Finnish National Board on Research Integrity TENK. Since the current study did not meet any of these requirements (e.g., intervening physical integrity), the statement was not requested. Informed consent was obtained from all participants before the experiment via a Qualtrics survey online (https://www.qualtrics.com/). Participants provided their electronic signatures on the online form and received their signed consent forms and vouchers by post (Finnish participants) or email (Chinese participants) after the experiment.

2.4. Data analyses

To analyze the relationships between musical expertise and DS forward or backward tasks performance, linear regression models were built with DS forward or backward scores as outcome measures and musical expertise and language background as predictors. Due to the significant differences on *Number of 2nd language* and *Education level*, between Chinese and Finnish speakers, these two variables were added as covariates in the models. Based on our hypothesis about the differential effect of participants' native language on the impact of musical expertise in WM performance, we further conducted separate linear regression models for the Finnish and Chinese participants, with musical expertise as a predictor and DS forward or backward scores as outcome measures. In addition, to further investigate the relationship between the years of music training and WM performance, linear regression models were also performed with the years of training as a continuous variable (combining both musician and nonmusician groups) predicting DS forward or DS backward with the Finnish and Chinese participants, respectively.

To investigate whether tone memory can potentially mediate the relationship between musical expertise and verbal WM, we performed a mediation analysis process by following the protocol proposed by Baron and Kenny (1986) as well as in agreement with the discussion by Shrout and Bolger (2002) and Zhao et al. (2010) (as illustrated in Fig. 2). First, we estimated the association between musical expertise and verbal WM as the *total effect* (path *c*). Then, we determined whether musical expertise was associated with tone memory (path *a*). Next, we determined whether the association between tone memory scores and verbal WM was significant while musical expertise is held constant (path *b*). Then, we determined whether the association between musical expertise and verbal WM was significant while tone memory is held constant, as the *direct effect* (path *c*′). Finally, we determined whether musical expertise has an indirect effect on DS tasks scores via tone memory (path *ab*). Confidence intervals (CIs) using the bias-corrected and percentile-based methods were constructed using bootstrapping (accounting for the related data) using 1000 replications.

All the above analyses were conducted in R statistical software version 4.1.3 (R Core Team, 2023). The mediation analysis was conducted with the *mediation* package (Tingley et al., 2014).

3. Results

Performance in the DS forward and backward tasks and the tone memory task of Chinese-speaking and Finnish-speaking musicians and nonmusicians are presented in Table 2. Fig. 3 visually displays the DS forward and backward performance in different groups.

3.1. Associations between musical expertise and DS forward scores

Results of linear regression with DS forward scores as the outcome measure and musical expertise and language background as predictors are shown in Table 3. Musicians tended to outperform nonmusicians in DS forward tasks (F (4, 83) = 33.43, $p < 0.001$, adjusted $R^2 = 0.599$; musical expertise as a predictor: β = 0.74, 95 % CI [−0.04–1.53], $p = 0.063$). Chinese speakers outperform Finnish speakers significantly in the DS forward task (β = 5.05, 95 % CI [3.76–6.35], $p < 0.001$).

Separate linear regression models for Finnish participants and Chinese participants indicated that Finnish musicians significantly outperformed Finnish nonmusicians in the DS forward task (F(3, 38) = 4.548, $p = 0.008$, adjusted $R^2 = 0.206$; musical expertise as a predictor:

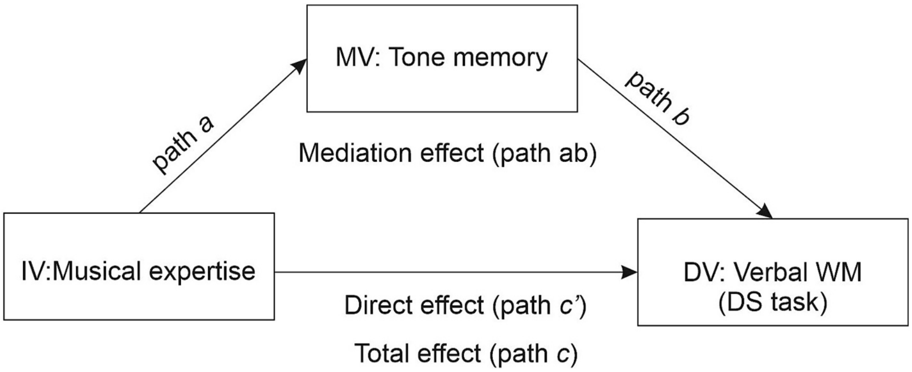

Fig. 2. Illustration of the mediation analysis. In the analysis, *Musical expertise* is the independent variable (IV); *Tone memory* is the mediating variable (MV); *Verbal WM* is the dependent variable (DV). Path *a* represents the association between musical expertise and tone memory; path *b* represents the association between tone memory and verbal WM; Path *c* represents the association between musical expertise and verbal WM; path *c*′ represents the association between musical expertise when controlling tone memory; path *ab* represents the estimated mediation effect of tone memory.

Table 2
Means and SDs of memory scores in the DS tasks and the tone memory tasks in Finnish-speaking and Chinese-speaking musicians and nonmusicians.

Task	Finnish speakers						Chinese speakers					
	Musicians			Nonmusicians			Musicians			Nonmusicians		
	N	*Mean*	*SD*	N	*Mean*	*SD*	N	*Mean*	*SD*	N	*Mean*	*SD*
Digit span forward	21	9.76	1.87	21	8.71	1.31	22	13.91	1.95	24	13.42	2.17
Digit span backward	21	7.95	1.8	21	7.1	1	22	11.64	2.48	24	12.17	2.5
Tone memory	20	1.63	0.53	19	0.71	0.47	19	2.38	0.62	23	1.2	0.81

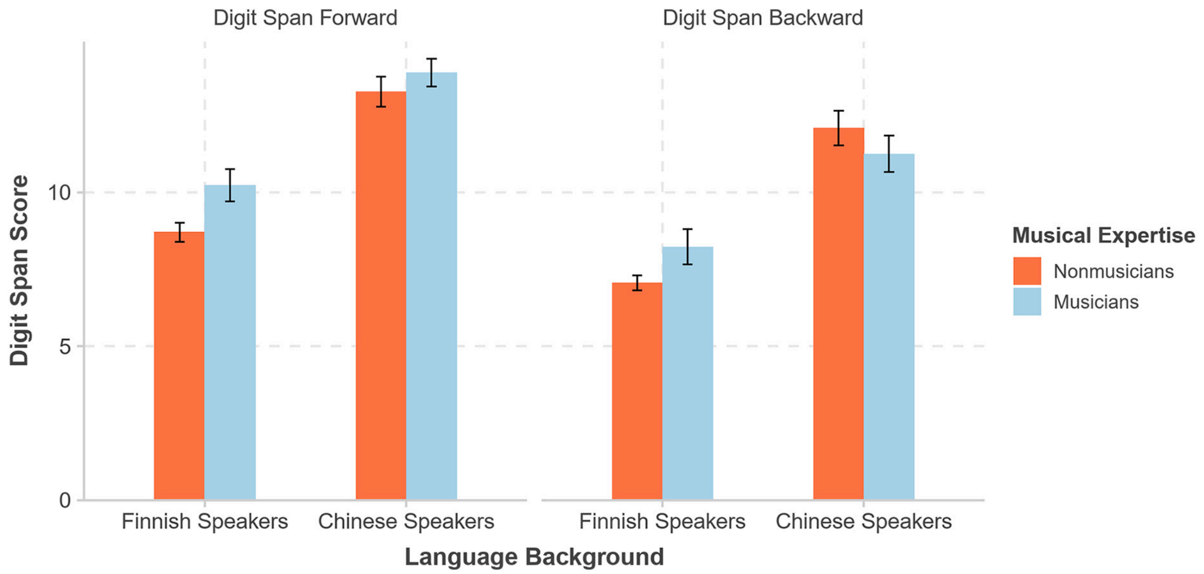

Fig. 3. Average DS forward (WM maintenance) and backward scores (WM manipulation) in Chinese-speaking and Finnish-speaking musicians and nonmusicians. Error bars represent 95 % CI.

Table 3
Results of regression models for musical expertise predicting DS forward scores with all participants, Finnish speakers, and Chinese speakers, respectively.

Predictors	Whole sample			Finnish speakers			Chinese speakers		
	Estimates	95 % CI	*p*	Estimates	95 % CI	*p*	Estimates	95 % CI	*p*
(Intercept)	9.15	7.10–11.21	**<0.001**	7.29	4.99–9.59	**<0.001**	15.26	12.82–17.70	**<0.001**
Music expertise	0.74	−0.04–1.53	0.063	1.13	0.18–2.07	**0.021**	0.6	−0.66–1.85	0.344
Language background	5.05	3.76–6.35	**<0.001**	–	–	–	–	–	–
Education level	−0.28	−0.61–0.04	0.088	−0.23	−0.64–0.17	0.243	−0.3	−0.81–0.21	0.235
N of 2nd Language	0.2	−0.25–0.66	0.381	0.62	0.14–1.10	**0.012**	−0.45	−1.31–0.41	0.294
Observations	88			42			46		
R^2/R^2 adjusted	0.617/0.599			0.264/0.206			0.079/0.013		

Note: *p* values smaller than 0.05 were marked in bold, indicating the corresponding effects are significant.

β = 1.13, 95 % CI [0.18–2.07], *p* = 0.021). However, in Chinese participants, musicians did not outperform nonmusicians in the DS forward task (F (3, 42) = 1.197, *p* = 0.323, adjusted R^2 = 0.013; musical expertise as a predictor: β = 0.6, 95 % CI [−0.66–1.85], *p* = 0.344).

3.2. *Associations between musical expertise and DS backward scores*

For DS backward scores as the outcome measure, results of linear regression are shown in Table 4. The linear regression analysis (F (4, 83)

Table 4
Results of regression models for musical expertise predicting DS backward scores with all participants, Finnish speakers, and Chinese speakers, respectively.

Predictors	Whole sample			Finnish speakers			Chinese speakers		
	Estimates	95 % CI	*p*	Estimates	95 % CI	*p*	Estimates	95 % CI	*p*
(Intercept)	6.86	4.52–9.21	**<0.001**	4.4	2.32–6.49	**<0.001**	12.85	9.87–15.84	**<0.001**
Music expertise	0.11	−0.78–1.01	0.802	0.79	−0.07–1.65	0.07	−0.3	−1.84–1.23	0.694
Language background	4.47	2.99–5.94	**<0.001**	–	–	–	–	–	–
Education level	0.11	−0.27–0.48	0.574	0.2	−0.16–0.57	0.266	0.03	−0.60–0.65	0.929
N of 2nd Language	0.06	−0.46–0.59	0.808	0.56	0.13–1.00	**0.012**	−0.67	−1.72–0.38	0.207
Observations	88			42			46		
R^2/R^2 adjusted	0.537/0.515			0.244/0.184			0.049/−0.019		

Note: *p* values smaller than 0.05 were marked in bold, indicating the corresponding effects are significant.

$= 24.1$, $p < 0.001$, adjusted $R^2 = 0.515$) did not reveal a significant effect of musical expertise ($\beta = 0.11$, 95 % CI [−0.78–1.01], $p = 0.802$). Chinese speakers outperform Finnish speakers significantly in the DS backward task ($\beta = 4.47$, 95 % CI [2.99–5.94], $p < 0.001$).

Separate linear regression models for Finnish participants and Chinese participants showed that Finnish musicians tended to outperform Finnish nonmusicians ($F(3, 38) = 4.084$, $p = 0.013$, adjusted $R^2 = 0.184$; musical expertise as a predictor: $\beta = 0.79$, 95 % CI [−0.07–1.65], $p = 0.07$). No differences were found between Chinese musicians and Chinese nonmusicians in DS backward task ($F(3, 42) = 0.721$, $p = 0.545$, adjusted $R^2 = -0.019$; musical expertise as a predictor: $\beta = -0.3$, 95 % CI [−1.84–1.23], $p = 0.694$).

The regression models, including years of musical training (instead of the binary coding 'musician' vs. 'nonmusician'), showed significant associations between the years of training and DS forward scores in Finnish-speaking participants ($F(3, 38) = 3.64$, $p = 0.006$, adjusted $R^2 = 0.216$; years of training as a predictor: $\beta = 0.057$, $t = 2.524$, $p = 0.016$), but not in Chinese-speaking or overall participants ($ps > 0.05$), as shown in Fig. 4. Similarly, significant associations was found between the years of training and DS backward scores in Finnish-speaking participants ($F(3, 38) = 5.08$, $p = 0.005$, adjusted $R^2 = 0.230$; years of training as a predictor: $\beta = 0.049$, $t = 2.442$, $p = 0.019$), but not in Chinese-speaking or overall participants ($ps > 0.05$),

3.3. *Mediation effects of tone sequence memory*

To investigate how tone sequence memory contributes to the effect of musical expertise on DS scores, mediation analyses were conducted 1) for all participants together and 2) separately for the Chinese and Finnish samples. This flow of analyses is based on a priori hypotheses about differences between Chinese and Finnish participants, due to their different language backgrounds.

3.3.1. *For all participants*

For the model using DS forward performance as DV: musicians outperformed nonmusicians in tone memory tasks, as path *a* in Fig. 5a ($p < 0.001$). Tone memory performance significantly predicted DS forward scores when holding musical expertise constant, as path *b* ($p = 0.018$). The relationship between musical expertise and DS scores (path *c* as total effect: $\beta = 0.732$, 95 % CI [−0.09, 1.56], $p = 0.082$) did not remain significant after controlling for the tone memory performance (path c' as direct effect: $\beta = -0.268$, 95 % CI [−1.42, 0.88], $p = 0.643$). The mediation effect of the tone memory was significant (path *ab* as indirect effect: $\beta = 1.000$, 95 % CI [0.15, 1.91], $p = 0.02$). The results indicated an indirect-only mediation (Zhao et al., 2010) – musical expertise benefits verbal WM storage by facilitating tone memory. Fig. 5a illustrates the mediation model with more detailed statistics.

For the model using DS backward performance as DV: musicians outperformed nonmusicians in tone memory task, as path *a* in Fig. 5b ($p < 0.001$). The tone memory performance significantly predicted the DS forward scores when holding musical expertise constant, as path *b* ($p = 0.004$). The insignificant relationship between musical expertise and DS backward scores (the total effects path *c*: $\beta = -0.046$, 95 % CI [−0.98, 0.89], $p = 0.923$), became significant after controlling for tone memory as a mediator, but to a negative direction (the direct effect path c': $\beta = -1.425$, 95 % CI [−2.7, −0.15], $p = 0.029$). The mediation effect of the tone memory was significantly positive, as the indirect path *ab* shows ($\beta = 1.379$, 95 % CI [0.23, 2.46], $p = 0.018$). The results indicated a competitive mediation (Zhao et al., 2010) – tone memory acted as a suppressor for the direct effect of musical expertise. Fig. 5b illustrates the mediation model with more detailed statistics.

3.3.2. *For Finnish and Chinese participants separately*

Illustrations of the mediation models are presented in Fig. 6. For Finnish participants, the mediation analysis showed a significant mediation effect of tone memory in both the model predicting DS forward scores (path *ab*: $\beta = 0.946$, 95 % CI [0.04, 2.07], $p = 0.04$) and the model predicting DS backward scores (path *ab*: $\beta = 1.008$, 95 % CI [0.24, 2.36], $p = 0.012$). The estimates of the relationship between musical expertise and DS scores (path c') decreased compared with the total effects (path c), although neither of the estimates was significantly different from 0 ($ps > 0.05$).

For Chinese participants, the mediation effect of the tone memory was significantly positive in the model predicting DS backward scores (path *ab*: $\beta = 1.964$, 95 % CI [0.17, 3.6], $p = 0.022$) and marginally significant positive in the model predicting DS forward scores (path *ab*: $\beta = 1.193$, 95 % CI [−0.13, 2.65], $p = 0.078$). Total effects in neither of the models was significantly different from 0 ($ps > 0.05$). However, the significance of the relationship between musical expertise and DS backward scores increased but became negative (path c': $\beta = -2.699$, 95

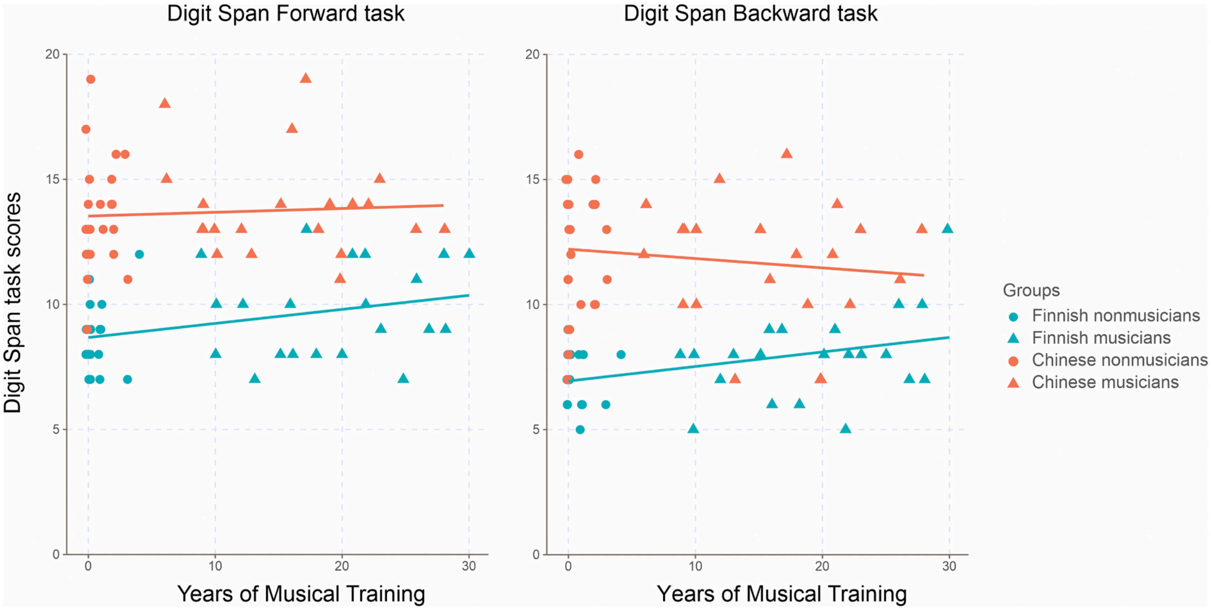

Fig. 4. The relationships between the years of musical training and digit span forward scores (WM maintenance, left) and backward scores (WM manipulation, right). The dots in round shape indicate the performances of nonmusicians and the dots in triangle shape indicate the performance of musicians.

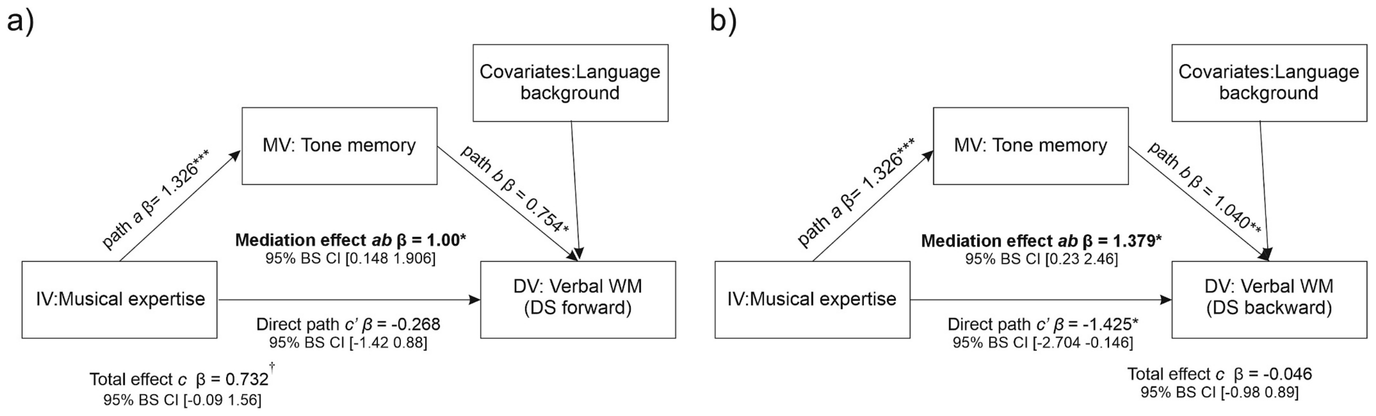

Fig. 5. a) Results of mediation analysis on the relationship between musical expertise and DS forward performance; b) results of mediation analysis on the relationship between musical expertise and DS backward performance. Path *c* represents the association between IV and DV; Path *a* represents the association between IV and MV; path *b* represents the association between MV and DV; path *c*′ represents the association between IV and DV when controlling the variation of MV; path *ab* represents the estimated mediation effect of MV in the relationship between IV and DV. *β* represents the coefficients of the effect of each path with language background as a covariate. Significance levels are indicated as follows: ***$p < 0.001$. **$p < 0.01$. *$p < 0.05$. †$p < 0.1$. 95 % BS CI = 95 % Bootstrapped Confidence Interval.

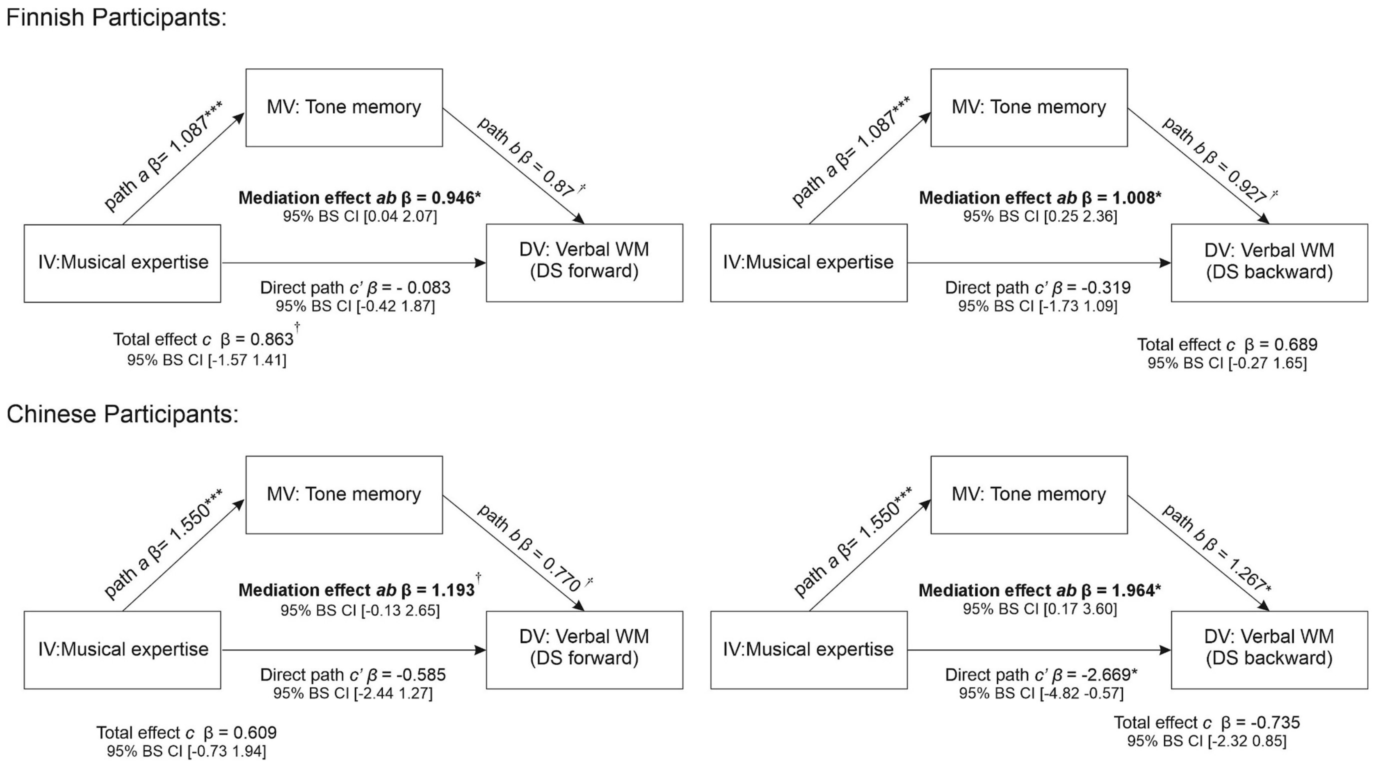

Fig. 6. Results of mediation analysis on the relationship between musical expertise and DS performance in Finnish participants and Chinese participants. Path *c* represents the association between IV and DV; Path *a* represents the association between IV and MV; path *b* represents the association between MV and DV; path *c*′ represents the association between IV and DV when controlling the variation of MV; path *ab* represents the estimated mediation effect of MV in the relationship between IV and DV. *β* represents the coefficients of the effect of each path. Significance levels are indicated as follows: ***$p < 0.001$. **$p < 0.01$. *$p < 0.05$. †$p < 0.1$. 95 % BS CI = 95 % Bootstrapped Confidence Interval.

% CI [−4.82, −0.57], $p = 0.014$), compared with the total effects (path c: $\beta = -0.735$, 95 % CI [−2.32, 0.85], $p = 0.356$).

4. Discussion

The present study investigated the association between musical expertise and verbal WM maintenance or manipulation, as indexed by DS forward and backward tests, respectively. We also investigated whether this association differs between participants with different native language backgrounds. Our findings suggested that musical expertise and verbal WM were associated in Finnish speakers, but not in Chinese speakers. Tone memory was identified as a mediator for the relationship between musical expertise and verbal WM.

4.1. Relationship between musical expertise and verbal WM maintenance

Finnish musicians outperformed Finnish nonmusicians in the DS forward task. The duration of musical instrument learning was also significantly associated with DS forward scores in the Finnish participants. These results indicate a more advanced verbal WM maintenance in Finnish musicians and those with longer learning experience in musical instruments. The results are consistent with previous studies, also conducted with speakers of non-tonal languages, such as Danish and Finnish (Hansen et al., 2013; Saarikivi et al., 2019). However, no significant differences were observed when comparing Chinese musicians and nonmusicians. The duration of music learning was not associated with verbal WM maintenance in the Chinese participants. These results echoed previous studies on tonal language speakers (Nie et al., 2022; Suárez et al., 2016).

The results of mediation analysis across all participants indicated that tone memory could be an underlying factor mediating the relationship between musical expertise and verbal WM maintenance. This finding helps identify the possible mechanism underlying the positive effect of musical expertise in WM. Musicians have enhanced tone memory due to their musical expertise, and the enhanced tone memory may facilitate sound encoding and memory processes for verbal stimuli. The observed tendency for advanced verbal WM maintenance in musicians was mediated by their tone memory. This suggests that musicians gain more advanced verbal WM via higher tone memory. In other words, for those musicians who fail to have enhanced tone memory, their verbal WM is not enhanced either. A mediation effect of tone memory was found in both Chinese and Finnish participants. In Mandarin Chinese, the lexical tones, which convey different meanings, share the same sound features with musical tones. Advanced memory for musical tones could benefit the memory processes of lexical tones and, consequently, facilitate verbal WM maintenance, although there was only trending mediation. Tone memory was also a significant factor in mediating the relationship between musical expertise and verbal WM maintenance in Finnish-speaking participants. This finding suggests that the overlapping processing of musical and verbal materials does not only benefit WM in tonal language speakers but also in non-tonal language speakers.

4.2. Relationship between musical expertise and verbal WM manipulation

Verbal WM manipulation refers to temporarily holding and manipulating the verbal stimuli in memory functions. It was measured by the DS backward task in the study. The results showed a tendency of Finnish musicians outperforming Finnish nonmusicians in the DS backward task. The duration of musical instrument training was significantly associated with DS backward task performance. However, no significant difference between musicians and nonmusicians was observed in DS backward task performance for Chinese-speaking participants. These findings on DS backward contrast with previous studies testing participants with a Chinese language background (Lee et al., 2007; Nie et al., 2022). This positive relationship between music training and DS backward in Chinese participants was mostly observed in children but not in adults (see Lee et al., 2007 for a cross-sectional study). Participants' age may be a potential influential factor, because the WM manipulation that requires central executive function may be influenced more easily by musical expertise in childhood compared with adulthood.

Mediation analysis revealed that tone memory suppressed the relationship between musical expertise and verbal WM manipulation. After separating the participants to Finnish and Chinese speakers, we found the suppression effect only in the Chinese sample. The total effect indicated that musicians and nonmusicians did not differ in their verbal WM manipulation performance. The suppression effect of tone memory suggests that the Chinese musicians with enhanced tone memory could perform in the verbal WM task at the same level as nonmusicians. Had the musicians failed to gain better tone memory, their performance in the verbal WM manipulation might have been worse than that of the non-musicians. The music training increased tone memory performance, which in turn benefited verbal WM manipulation. As a result, the potential adverse effect of musical expertise and the positive indirect effect via tone memory canceled each other out, leading to a "null relationship" as a total effect in Chinese participants. For Finnish participants, the mediation effect of tone memory for predicting verbal WM manipulation mirrors the mediation effect for predicting verbal WM maintenance. Finnish musicians exhibited more advanced maintenance of tone sequences than nonmusicians, which consequently facilitated the manipulation performance of verbal materials in WM. Had the Finnish musicians failed to gain better tone memory, they may have had the same level of verbal WM manipulation as Finnish non-musicians.

4.3. Comparing the effects of musical expertise and verbal WM between Finnish and Chinese speakers

Based on the above discussions, the findings indicated that the musical expertise was significantly associated with verbal WM in Finnish speakers, but not in Chinese speakers. This discrepancy applied to both the maintenance and manipulation processes in the verbal WM. Tone memory mediated the relationship between musical expertise and verbal WM maintenance in both language groups, even though the association was not significant for Chinese speakers. In contrast, the mediating role of tone memory on verbal WM manipulation differed: unlike Finnish participants who had enhanced verbal WM from musical expertise via superior tone memory, the Chinese participants may already be equipped with good enough verbal WM manipulation no matter if they are musicians or nonmusicians. The musical expertise and enhanced tone memory can benefit the verbal WM of those who did not have sufficient manipulation functions (e.g., children, professionals who do not need manipulation skills as a pre-requisite). Yet, for those who have already developed better verbal WM by other means, musical expertise and tone memory may have limited effects.

Interestingly, the Chinese participants, regardless of musical expertise, outperformed Finnish participants in both DS forward and backward tasks, which represent verbal WM maintenance and manipulation, respectively. These advantages in Chinese speakers over other language speakers echo previous findings on DS forward performance in children (Chen & Stevenson, 1988; Stigler et al., 1986) and both DS forward and backward performance in adults (Chen et al., 2009). One common explanation for this advanced DS performance in Chinese speakers was that the articulation time is shorter in Chinese language, which may reduce WM load (Chen et al., 2009; Stigler et al., 1986). In the case of the present study, to account for this difference, we tried to balance the pronunciation time of the digit between Finnish and Chinese, by presenting each digit for exactly one second. Another hypothesis attributed the advantage to Chinese's shorter syllable length, which was linked to faster speech production and better short-term recall (Chen et al., 2009). This may explain the significant differences in DS performance in the current study between Finnish and Chinese participants, as the Finnish digits have two to three syllables, whereas the Chinese digits always have one syllable. For example, the digit "eight" is "kahdeksan" (kah-dek-san) in Finnish and "bā" in Chinese. Furthermore, according to the present findings regarding the link between tone memory and verbal WM, we speculate that the enhanced DS scores in Chinese speakers may be attributed partially to their more advanced tone memory from the tone language experience, compared to the Finnish speakers. Future studies may be required to test this hypothesis including more languages, with comparable syllable length.

4.4. Limitations

Several limitations should be considered in the present study. First of all, due to practical issues, only a cross-sectional study was conducted. Thus, we want to be cautious when making conclusions about any causal relationship between the background of the participants and their WM performance. Yet, it needs to be acknowledged that it can be hard or even impossible to implement longitudinal studies with the same training settings, long enough training programs, large enough number of participants, and balanced characteristics of participants in two countries with different language backgrounds in parallel. Moreover, although we aimed to compare participants with tonal language backgrounds and nontonal language backgrounds, only Chinese and Finnish participants were compared in the current research. Nevertheless, these languages represent two extreme categories of tonal and quantity languages and thus offer a good starting point. Furthermore, our sample size was relatively small due to the recruitment challenges during the COVID-19 pandemic and the difficulty in finding the target groups online in two countries. Thus, the findings from the present study should be viewed as preliminary and thus inviting for future studies. Ideally, they should involve larger and more diverse samples, preferably also additional language groups, to confirm and extend our findings. Lastly, again due to the pandemic situation, laboratory-based experimentation was not possible when collecting the data. Thus, the study was carried out via online platforms. Technical issues, e.g., audio signal quality, possible internet problems, uncontrolled environmental noise, etc., could not be avoided (Bridges et al., 2020; Reips, 2002; Sauter et al., 2020). However, it is important to note that we adopted measures aiming to minimize the difference with the face-to-face experiments. In contrast to common procedures of online studies on the Internet without an experimenter, we combined online data collection with monitoring by the experimenter. This thus provides a new, better-controlled alternative to conducting psychological experiments, particularly when collecting cross-cultural behavioral data across different countries.

5. Conclusion

This study reveals that musical expertise enhances verbal WM in native Finnish speakers. This pattern was not observed in native Chinese speakers. Tone memory mediated the relationship between musical expertise and verbal WM in both Finnish and Chinese speakers. These findings highlight the interplay between musical training, language background, and auditory processing. They encourage taking native language background into account in empirical studies to understand the cognitive benefits of musical expertise.

CRediT authorship contribution statement

Peixin Nie: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Barbara Tillmann:** Writing – review & editing, Resources, Conceptualization. **Vesa Putkinen:** Writing – review & editing, Validation. **Caitlin Dawson:** Writing – review & editing, Conceptualization. **Sha Tao:** Writing – review & editing, Resources. **Mari Tervaniemi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2025.105576.

Data availability

All data, stimuli of the tone memory task, and code for data analysis in this paper are available on the OSF page: https://osf.io/mr3yp/?view_only=abe12268f29c4782a09b9eca1649ffd8.

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