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# Sensorimotor Impairment in Ageing and Neurocognitive Disorders: Beat Synchronisation and Adaptation to Tempo Changes

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## AGEING, NCD, AND BEAT SYNCHRONISATION

### 1 **Sensorimotor Impairment in Ageing and Neurocognitive Disorders: Beat Synchronisation and** 2 **Adaptation to Tempo Changes**

3  
4 Running head: AGEING, NCD, AND BEAT SYNCHRONISATION

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### 1 **ABSTRACT**

2 **Background:** Understanding the nature and extent of sensorimotor decline in ageing  
3 individuals and those with neurocognitive disorders NCD, such as Alzheimer's disease, is  
4 essential for designing effective music-based interventions.

5 **Objective:** Our understanding of rhythmic functions remains incomplete, particularly in how  
6 ageing and NCD affect sensorimotor synchronisation and adaptation to tempo changes. This  
7 study aims to fill this knowledge gap.

8 **Methods:** Patients from a memory clinic participated in a tapping task, synchronising with  
9 metronomic and musical sequences, some of which contained sudden tempo changes. After  
10 exclusions, 51 patients were included in the final analysis.

11 **Results:** Participants' mini-mental state examination scores were associated with tapping  
12 consistency. Additionally, age negatively influenced consistency when synchronising with a  
13 musical beat, whereas consistency remained stable across age when tapping with a metronome.

14 **Conclusions:** The ability to extract a beat from a musical signal diminishes with age, whereas  
15 the capacity to maintain a beat remains relatively constant. However, both processes may  
16 decline at moderate or severe stages of NCD. Moreover, the results indicate that the initial  
17 decline of attention and working memory with age may impact perception and synchronisation  
18 to a musical beat, whereas progressive NCD-related cognitive decline results in more  
19 widespread sensorimotor decline, affecting tapping irrespective of audio type. These findings  
20 underline the importance of customising rhythm-based interventions to the needs of older adults  
21 and individuals with NCD, taking into consideration their cognitive as well as their rhythmic  
22 aptitudes.

23 This study was registered at [clinicaltrials.gov](https://clinicaltrials.gov) (NCT04146688).

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- 1 Keywords: aging, dementia, Alzheimer's disease, music, neurodegenerative diseases, auditory
- 2 perception

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### 1 INTRODUCTION

#### 2 *Neurocognitive disorders and music-based interventions*

3 Neurocognitive disorders (NCD) are acquired disorders marked by a progressive decline in  
4 cognitive functioning, particularly with regards to memory, but also including domains like  
5 attention, language, learning, and social cognition, challenging the patients' capacity to live  
6 autonomously [1]. Before the fifth edition of the Diagnostic and Statistical Manual of Mental  
7 Disorders (DSM-5), major NCD was referred to as dementia, but we will use the term NCD in  
8 this article. Different forms exist, such as Alzheimer's disease (AD), vascular NCD, NCD with  
9 Lewy bodies, and others. In the same vein, minor NCD is a DSM-5 diagnosis corresponding to  
10 a milder or prodromal form of the disease, which generally does not impede autonomy, and  
11 which was referred to as mild cognitive impairment before. In the absence of a cure for NCD,  
12 there is promise in improving the quality of life of those affected by enhancing various aspects  
13 of their well-being through non-pharmacological interventions. Among these interventions,  
14 music-based approaches have shown considerable potential in this regard. It has been suggested  
15 [2–4] that they may be particularly effective if they stimulate sensorimotor synchronisation  
16 (SMS), defined as the temporal coordination of rhythmic movement with an external rhythm  
17 [5]. This may be related to temporal expectations elicited by a musical beat, which may  
18 stimulate the reward network and induce pleasure [6]. Besides directly eliciting reward and  
19 pleasure, stimulating rhythmic abilities may have positive effects on the way people with NCD  
20 interact with and adapt to their environment. Improving temporal prediction abilities might help  
21 people synchronise and interact with others [7], improve communication, and reduce isolation.

#### 22 *Sensorimotor synchronisation*

23 In SMS research, individuals coordinate their movements with an auditory sequence, typically  
24 involving a simple metronome or music. Synchronisation performance is typically assessed in

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1 terms of consistency and asynchrony. Consistency refers to the degree of variability in the time  
2 differences between taps and beats, whereas asynchrony refers to whether participants tapped  
3 before (negative asynchrony) or after (positive asynchrony) the pacing event [8]. Paced tapping  
4 to a metronome and paced tapping to music, while ostensibly the same task, may in fact engage  
5 different mechanisms. In a metronomic sequence, the beat is indicated as simple regular tones,  
6 whereas in music, the beat is embedded within a complex auditory pattern. In this context, it is  
7 useful to think of beat perception as being comprised of two subprocesses; beat induction (beat  
8 finding), where an underlying beat is inferred even when auditory events are unequally spaced  
9 [9,10]; and beat maintenance (beat continuation), which is a more implicit and mechanical  
10 process that implies continual, sustained measurement of predictable intervals and is less  
11 dependent on attention [10,11]. Likely, both processes are employed simultaneously, the  
12 relative dependence of each depending on the saliency of the beat. Tapping to a metronome,  
13 then, might employ primarily beat maintenance processes, whereas tapping to music may be  
14 more dependent on beat induction. As a result, tapping to music is often associated with higher  
15 difficulty, expressed in lower tapping consistency [12–14], but not all studies have confirmed  
16 this [8,15]. Indeed, the difficulty of performing synchronous movement to music presumably  
17 depends primarily on the clarity of its beat. In terms of asynchrony, people tend to tap ahead of  
18 the beat (referred to as mean negative asynchrony) when synchronising with a metronome but  
19 not with music [8,12–14,16]. The mechanisms underlying this phenomenon are still not fully  
20 understood.

21 A key process in SMS is error correction. While error correction is an ever-present mechanism  
22 without which one would gradually become out of sync [17], it can directly be tested by  
23 introducing tempo changes. Adapting to tempo changes requires attention, awareness and some  
24 memory for at least the preceding events [18], and is likely related to cognitive flexibility, the  
25 ability to shift between mental sets and strategies [19].

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1 *How do age and neurocognitive disorders impact sensorimotor synchronisation?*

### 2 Ageing

3 The ability to perceive a beat and synchronise to it emerges early in life, remains relatively  
4 stable in adulthood [20,21], and may be preserved in old age, at least when synchronising with  
5 an evenly spaced beat at a comfortable tempo [22–25]. Nonetheless, certain studies have  
6 indicated a decline of sensorimotor abilities associated with age, which seems to appear above  
7 the age of 75 [20,21,26] (however, see [27] for a study demonstrating a reduction in tapping  
8 performance even in relatively young older adults). However, there remains a lack of research  
9 studying SMS in the latest decades of life. Importantly, another study [28] did not find age-  
10 related differences in simple SMS, but older participants' performance was diminished when  
11 participants had to simultaneously perform a cognitively challenging task while tapping to a  
12 metronome. This suggests that older people may employ more attention and working memory  
13 resources when tapping at a comfortable tempo.

14 The aforementioned studies examined the effect of age on SMS using metronomes. To our  
15 knowledge, the influence of old age on SMS with *music* has not yet been tested. However,  
16 considering the typical decline in attentional capacities associated with ageing [29,30], it is  
17 reasonable to speculate that beat induction may be more vulnerable to age-related decline than  
18 beat maintenance, which would result in age-related declines in SMS performance particularly  
19 with music.

### 20 Neurocognitive disorders

21 Several studies have indicated that SMS abilities tend to be relatively preserved in individuals  
22 with NCD when instructed to tap along with a metronome set to a comfortable tempo [31].  
23 However, differences were observed when participants had to continue tapping after an external  
24 sequence had ended [22,32] or when the target rate deviated substantially from their

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1 comfortable tempo [22,33,34], manipulations likely to engage working memory and attention.  
2 However, a recent study by Hobeika et al. [35] revealed a decline in performance among  
3 individuals with major NCD in tapping even at a comfortable rate with a metronome and with  
4 music, and a negative relationship between consistency during metronome tapping and  
5 participants' score on the mini-mental state examination (MMSE) [36], a brief screening tool  
6 for assessing NCD. These different results may be explained by the severity of NCD in Hobeika  
7 et al.'s study (their NCD group had a mean MMSE of 15.5, which was lower than in the other  
8 studies). However, definite conclusions cannot be drawn from Hobeika et al.'s study because  
9 they pooled together participants who were tested under different conditions, which emphasises  
10 the need for the current study, investigating the impact of NCD severity under homogeneous  
11 testing conditions.

12 It may be that in healthy ageing people, or mild forms of NCD, tapping with a metronome may  
13 be a largely automatic process, and only when tapping with music, or in cognitively challenging  
14 paradigms are attention and working memory processes recruited, leading to a decline in  
15 performance. However, for people at more severe stages of NCD, attention and working  
16 memory are needed even to synchronise at a comfortable pace with a metronome. Indeed, some  
17 research has demonstrated increased use of non-motor regions during simple motor tasks in  
18 NCD, at least in AD [37,38], indicating that with increasing severity of the disease, individuals  
19 employ other domain-general brain networks during SMS, reflecting a shift to more effortful  
20 and less automatic processing of rhythm, and potentially lower performance due to increasing  
21 competition for limited cognitive resources. It is possible that individuals in moderate to severe  
22 stages of NCD may require more attention and working memory even for tapping with simple  
23 metronomic sequences, and may be more impaired in these cognitive abilities, resulting in a  
24 general sensorimotor impairment manifested by reduced consistency when tapping to any  
25 regular stimulus, be it a metronome or music.



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1 Similar to synchronisation-continuation tapping and tapping at tempi far from one's  
2 comfortable rate, tapping with a sequence containing tempo changes may particularly involve  
3 attention and working memory [18]. A particular impairment in SMS with tempo changes has  
4 already been demonstrated in other clinical populations, namely, people with traumatic brain  
5 injury [39], autism spectrum disorder [40], basal ganglia pathology [41], and cerebellar lesions  
6 [42], and has been explained in terms of attention-dependent temporal processing. Since  
7 attention is greatly impaired in people with NCD [43], the ability of people with NCD to adapt  
8 their tempo when encountering tempo changes may be compromised, due to an imprecise  
9 representation of temporal structure and inefficient allocation of attention over time [41].  
10 Finally, a decline in cognitive flexibility found in people with NCD [44,45] may present another  
11 contributing factor to their potential disadvantage in adaptation to tempo changes. To our  
12 knowledge, there does not exist any research examining the effect of NCD on tempo adaptation  
13 in SMS. It is important to investigate this aspect, as adaptation to tempo changes can serve as a  
14 model for understanding how individuals interact with a dynamically changing environment in  
15 general.

### 16 *The current study*

17 The aim of the current study was to test the effects of age and NCD severity on SMS to  
18 metronomes and to music with and without tempo changes, in a group of patients at a French  
19 memory clinic, most of whom had major or minor NCD of diverse aetiologies. In this context,  
20 we examined SMS skills, with particular emphasis on the impact of tempo changes by  
21 introducing sudden accelerations and decelerations every 15 seconds in half of the trials, and  
22 computing consistency and asynchrony. The difficulty in this task should come only from the  
23 changes in tempo, rather than presenting participants with inherently difficult tempi for  
24 synchronisation. To achieve this, we selected base tempi that closely aligned with the typical  
25 spontaneous motor tempo reported in the literature for older adults [21,25] and we confirmed

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1 this by assessing individuals' spontaneous tempo. In traditional SMS paradigms, participants  
2 typically tap their finger or hand to an auditory regular beat. However, when applying such  
3 paradigms to individuals with NCD, particularly in advanced stages, special consideration is  
4 required to avoid stressful, unpleasant or artificial laboratory situations, as they might find it  
5 difficult to cope with such conditions, and they may experience difficulties in retaining and  
6 following instructions, especially in longer experiments. For these reasons, tasks with  
7 multimodal stimuli, creating a quasi-social situation, may be conducive [46,47]. Additionally,  
8 people, including older adults with NCD, might actually perform better when synchronising  
9 with a video than with another person [14,48]. We recently developed and validated an  
10 experimental setup tailored to elderly individuals [14,48,49] and continue its use to present  
11 stimuli bimodally (audio plus video). Using this experimental design and assessing a group of  
12 older adults exhibiting a range of ages and varying levels of cognitive impairment created an  
13 optimal setting for examining the distinct impacts of both age and NCD on sensorimotor  
14 synchronisation.

### 15 Hypotheses

16 Firstly, we expect a global impairment in SMS with increasing NCD severity. Specifically, we  
17 expect that MMSE score will have a negative impact on tapping consistency. Additionally, we  
18 hypothesise that consistency will be lower in trials with a shifting tempo compared to those  
19 with a stable tempo. More importantly, we predict an interaction between the presence or  
20 absence of tempo changes and MMSE score, such that the reduction in consistency in the  
21 shifting condition will be more pronounced in individuals with a lower MMSE score, probably  
22 due to declines in attention, working memory, and cognitive flexibility. Consistent with  
23 previous research, we expect lower consistency when individuals synchronise their movements  
24 with music compared to a metronome [12–14]. Furthermore, due to increased reliance on beat  
25 induction with music and decreased attentional capacities with ageing, we expect consistency

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1 to decrease with age when individuals tap with music, but to a lesser extent (or not at all) with  
2 a metronome. Finally, we hypothesise that asynchrony will be lower (more negative) in the  
3 metronome conditions compared to music [5,8,12–14,50].

### 4 MATERIALS AND METHODS

#### 5 *Participants*

6 A total of 61 patients were recruited at the geriatric day hospital *Les Bateliers* (Lille University  
7 Hospital, France), during a scheduled consultation related to memory problems or falls.  
8 Inclusion criteria included age between 60 and 99, right-handedness and native or near-native  
9 fluency in French. Patients were ineligible for participation if they had Parkinson's disease,  
10 other motor disorders or paralysis, or uncorrected hearing or vision problems. Patients' data  
11 were excluded from analysis if they did not finish the experiment. Their diagnosis of major  
12 NCD, minor NCD, or absence of NCD was made by a geriatrician and based on DSM-5 criteria  
13 [1]. However, in this study, we assessed cognitive impairment as a continuous variable using  
14 the MMSE. After ten exclusions (seven who withdrew from the study during the experiment,  
15 one due to technical problems, one who tapped in a seemingly random fashion as indicated by  
16 Rayleigh's test [51], and one whose MMSE score of 14 was an outlier; 3 SDs below the mean),  
17 51 patients were included in this study. The data were collected between November 2021 and  
18 July 2022. The study was approved by the local Ethics Committee (Comité de Protection des  
19 Personnes, Sud-Est VI, France; No. 2017-A03543-50) and by the Commission Nationale de  
20 l'Informatique et des Libertés, registered at [clinicaltrials.gov](https://clinicaltrials.gov) (NCT04146688). All patients  
21 provided written informed consent for their participation in accordance with the Declaration of  
22 Helsinki.

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### 1 *Materials*

#### 2 Experimental apparatus

3 The experimental set-up consisted of a chair for the patient with a tapping tablet attached to the  
4 right armrest [46,47]. A life-sized screen (158 x 92 cm) and a pair of loudspeakers were placed  
5 in front of the patient at a distance of 230 cm. A video of a musician tapping to the  
6 simultaneously presented auditory sequence was projected onto the screen during the task in  
7 front of the patient. Each patient was tested individually and was separated from the  
8 experimenter by a curtain to avoid distraction. Stimuli were presented and responses collected  
9 using a programme written in MAX/MSP (<https://cycling74.com>).

#### 10 Stimuli

11 Stimuli were 75 seconds long and consisted of either a metronome or a musical sequence and  
12 a video recording of the musician tapping to the beat of the auditory sequence. Both types of  
13 audio were preceded by 4 beats to provide the tempo.

14 Metronome trials consisted of regular beats. For the music trials, a custom-made rendition of  
15 an excerpt of the French popular song “Non, je ne regrette rien” by Édith Piaf was used. This  
16 particular song was chosen because it was likely well-known to our age group and its original  
17 tempo is close to older adults’ spontaneous motor tempo [14,25]. A MIDI version of the song  
18 (without lyrics), available in an online music repository ([www.midis101.com](http://www.midis101.com)) was selected and  
19 cropped to a length of 75 s. We opted for a MIDI version of the song in order to have completely  
20 isochronous timing and the possibility to manipulate its tempo.

21 The musical and metronomic sequences were manipulated to conform to one of four temporal  
22 patterns (Figure 1): A stable IOI of 674 ms (A), a stable IOI of 741 ms (B), or a sequence in  
23 which the tempo shifted every 15 seconds between the two, starting either at 674 ms (C) or  
24 starting at 741 ms (D). Ableton Live was used to render the musical stimuli from the MIDI

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1 versions using their in-house instruments, to create the metronomic stimuli and to perform the  
2 tempo manipulations. The visual part of the audio-visual stimuli was created beforehand by  
3 filming the musician who sat in the position of the participants, listened to the musical stimuli  
4 and tapped along. An analysis of the musician's tapping consistency and asynchrony during the  
5 recording of these videos indicated very good performance and minimal error (see Table S1).

6 ----Insert Figure 1-----

### 7 *Procedure*

8 The experiment started by orally administering a musical expertise questionnaire, which  
9 inquired about participants' musical training, listening habits, and engagement with music.  
10 Then, short forms of the Geriatric Depression Scale [52] and the Geriatric Anxiety Inventory  
11 [53] were orally administered. Next, each patient performed a brief spontaneous motor task by  
12 tapping as regularly as possible for 31 taps (30 inter-tap intervals; ITIs), at their preferred,  
13 comfortable tempo.

14 Afterwards, each patient underwent the paced tapping task, in which they were exposed to  
15 bimodal stimuli (described in the preceding section) and tapped along with every beat, just like  
16 they watched the musician do in the video. A practice trial was followed by eight experimental  
17 trials, counterbalanced across participants, in a randomized order. The participant was not  
18 informed that tempo changes might occur. The patient was given the possibility to take a break  
19 after half of the experimental trials.

### 20 *Data analysis*

#### 21 Calculation of SMS variables

22 For the 30 intervals produced during the spontaneous motor task, we calculated mean ITI and  
23 CV (standard deviation divided by mean) of ITI. In the paced tapping task, as we mentioned

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1 above, the tempo either remained stable or shifted every 15 seconds. This allowed us to analyse  
2 responses per 15-second segment to explore the impact of three within-subjects variables, each  
3 with two levels: audio (music/metronome), tempo (fast/slow), and tempo stability  
4 (stable/shifting; Figure S1A).

5 Consistency and asynchrony were computed using circular statistics [54] with the CircStat  
6 toolbox [55] in MATLAB [56]. We opted for circular analysis of synchronisation data as this  
7 allowed for a robust analysis even in the case of missing or superfluous taps, as asynchronies  
8 and their variability can be computed without necessarily attributing each response event to a  
9 particular beat [57]. In a given trial, ms in an inter-onset interval (IOI) are converted into  
10 degrees on a circular scale going from  $-180^\circ$  to  $+180^\circ$ . The beat's onset is at  $0^\circ$ , the time a  
11 participant would be expected to tap. An angle of  $180^\circ$  would indicate a participant tapping in  
12 antiphase. Vectors were averaged to obtain a mean resultant vector  $\vec{R}$  [54,55] allowing for the  
13 calculation of synchronisation consistency and asynchrony. Consistency is represented by the  
14 length of the vector  $\vec{R}$  and ranges from 0 to 1, where 1 corresponds to perfect consistency (all  
15 taps occurred with the same delay to the beat) and 0 describes a situation where taps were  
16 randomly distributed between the beats. Asynchrony reflects the angular deviation ( $\theta$ ) of vector  
17  $\vec{R}$  from 0, which is then transformed back into ms (Figure 2). Consistency and asynchrony were  
18 only analysed for the segments 2 through 5, as performance in the first segment was not  
19 pertinent to us since no tempo change would have occurred in this segment, even in the shifting  
20 condition (see Figure S1B).

21 ----Insert Figure 2-----

### 22 Statistical analyses

23 All statistical analyses were performed in R 4.2.2 using RStudio [58,59]. We analysed SMS  
24 consistency and asynchrony by conducting mixed-effects models. In both cases, fixed effects

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1 included the four within-subject factors (audio, tempo, tempo stability, and segment) as well as  
2 the between-subjects variables age and MMSE. We added to both models the four-way  
3 interaction between audio, tempo, tempo stability, and segment, the four-way interaction  
4 between audio, tempo, tempo stability, and age, the four-way interaction between audio, tempo,  
5 tempo stability, and MMSE, as well as all lower-order interactions and main effects.  
6 Furthermore, we controlled for the effects of gender, years of education, musical expertise, and  
7 condition order by entering them as additional fixed effects in the model. Finally, participant  
8 was entered as a random effect. In the analysis with consistency as a dependent variable, a  
9 generalised linear mixed model with a beta distribution and a logit link was performed using  
10 the glmmTMB package [60] in R. In the analysis with asynchrony as a dependent variable, we  
11 first filtered out segments with insufficient taps (i.e., where the percentage of taps relative to  
12 the number of beats was more than 2 standard deviations below the mean). Then, we  
13 transformed the variable asynchrony by taking the cubic root of its absolute value and  
14 multiplying it with its original sign. This was done to fulfil the assumption of normality of  
15 residuals, as asynchrony was right-skewed. Then, we performed a linear mixed-effects model  
16 analysis using the lme4 package [61]. Type II Wald chi-square tests were used to test the main  
17 effects and interactions. We present effect size by computing  $f^2$ , which is considered an  
18 appropriate metric of effect size in mixed-effects regression models [62]. Only the significant  
19 highest-order interactions are presented and discussed even if they contain lower-order  
20 significant effects; however, the complete results of the two analyses are detailed in Tables S3  
21 and S4. None of the significant effects including segment will be presented in the results section  
22 to focus on the effects of interest.

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### 1 RESULTS

#### 2 *Participants*

3 Demographic data, including age, gender, and education, and clinical data, encompassing  
4 diagnosis, MMSE, activities of daily living [63], instrumental activities of daily living [64],  
5 Geriatric Depression Scale, and Geriatric Anxiety Inventory, can be found in Table 1. Of the  
6 21 participants diagnosed with major NCD, nine were diagnosed with AD, two with vascular  
7 NCD, 11 with NCD of mixed aetiology, and one with NCD of an unknown origin. A  
8 distribution of MMSE scores is shown in Figure S2. Demographic and clinical data of the seven  
9 participants who withdrew from participation during the study can be found in Table S2. The  
10 participants who did not finish the study were on average older ( $U = 66.0$ ,  $p = .007$ , Mann-  
11 Whitney U test) and had a lower MMSE score ( $U = 265.5$ ,  $p = .038$ , Mann-Whitney U test)  
12 than those who did, whereas the two groups did not differ in terms of gender, diagnosis,  
13 education, musical expertise, ADL, IADL, depression, or anxiety (all  $p > .05$ ). Moreover, all  
14 participants who finished the study prematurely were diagnosed with major NCD. To ensure  
15 that the tempo of the experimental stimuli (674 ms and 741 ms) was within a comfortable range,  
16 participants' mean spontaneous motor tempo was computed, which was 715 ms (SD = 468 ms).

17 -----Insert Table 1-----

#### 18 *Consistency*

19 The results of the generalised linear mixed model are presented in Table S3. A main effect of  
20 MMSE (Wald  $\chi^2 = 4.06$ ,  $p = .044$ ,  $f^2 = 0.03$ ) suggests that more cognitively impaired people  
21 (i.e., with a lower MMSE score) tapped with a lower level of consistency (Figure 3A).  
22 Furthermore, there was a significant interaction of audio and age (Wald  $\chi^2 = 7.06$ ,  $p = .008$ ,  $f^2$   
23  $< 0.01$ ; Figure 3B). The slope of music was negative and significantly different from zero ( $p =$



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1 .046), whereas the slope of metronome was not ( $p = .433$ ). In other words, consistency  
2 decreased with age, but only in the music conditions.

3 ----Insert Figure 3-----

4 Additionally, there was a three-way interaction effect of audio, tempo, and tempo stability  
5 (Wald  $\chi^2 = 0.02$ ,  $p = < 0.001$ ; Figure 4A). We conducted post hoc tests for the 12 relevant  
6 pairwise comparisons: Conditions were compared in which two of the variables remained  
7 constant while the third varied (e.g., music/fast/stable versus music/fast/shifting). Statistical  
8 significance was adjusted for multiple comparisons using the Benjamini-Hochberg method.  
9 Across conditions, consistency was higher in metronome compared to music trials, and in trials  
10 with a stable tempo compared to those with a shifting tempo. Regarding tempo, consistency did  
11 not differ between segments with a fast versus slow tempo, with one notable exception: In  
12 metronome trials with a shifting tempo, consistency was higher when the tempo was slow (i.e.,  
13 following a deceleration) compared to when it was fast (i.e., following an acceleration; mean  
14 difference estimate  $\pm$  standard error:  $0.03 \pm 0.03$ ). Finally, there were a two-way interaction  
15 effect of tempo stability and age, and a three-way interaction between audio, tempo, and  
16 MMSE. These effects were the two smallest effects ( $f^2 < .002$ ) and it is unlikely they have  
17 practical significance. We therefore report these effects only in the Supplementary Information  
18 (Figures S3 and S4).

19 ----Insert Figure 4-----

### 20 *Asynchrony*

21 The results of the linear mixed model are presented in Table S4. There was a significant three-  
22 way interaction between audio, tempo, and tempo stability (Wald  $\chi^2 = 15.15$ ,  $p < .001$ ,  $f^2 = 0.02$ ;  
23 Figure 4B). As in the analysis of consistency, pairwise comparisons were conducted and  
24 statistical significance adjusted using the Benjamini-Hochberg method. All of the 12 pairwise

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1 comparisons yielded statistically significant results ( $p < .05$ ), indicating significant differences  
2 among the means. When the tempo was stable, participants anticipated the stimuli more when  
3 tapping with a metronome than with a musical beat. When tapping to a sequence with a shifting  
4 tempo, we appear to see the interaction of two phenomena. On the one hand, people's taps  
5 generally tended to occur somewhat later (higher or positive asynchrony) after an acceleration  
6 and somewhat before (lower or negative asynchrony) after a deceleration, which is to be  
7 expected: After a perturbation, participants' taps may still correspond to the pre-perturbation  
8 tempo before they adapt to the changed tempo. On the other hand, just like when tapping with  
9 a stable tempo, people's responses when tapping with a metronome occurred earlier than when  
10 tapping with music.

11 Moreover, there were a significant interaction of audio and MMSE, and a significant interaction  
12 of tempo stability and MMSE. Once again, these are the smallest effects (both  $f^2 < 0.001$ ),  
13 unlikely to have any practical significance despite their being statistically significant, and they  
14 can be found in the Supplementary Information (Figures S5 and S6).

## 15 DISCUSSION

16 The purpose of this study was to investigate the influence of age and NCD severity on SMS  
17 performance, quantified as tapping consistency and asynchrony. We were particularly  
18 interested in whether different subprocesses of SMS, including beat induction, beat  
19 maintenance, and error correction, might be differentially impacted by age and NCD. This  
20 differential impact could manifest in age and NCD unequally influencing SMS performance  
21 when synchronising with music versus metronomes, and with tempo-changing sequences  
22 compared to sequences with a stable tempo. We demonstrated that tapping consistency  
23 decreased with MMSE, providing evidence of the impact of neurocognitive disorders on  
24 sensorimotor abilities and thereby confirming our hypothesis. Contrary to our other hypothesis,

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1 however, the effect of MMSE did not depend on tempo stability. Additionally and as predicted,  
2 we observed a decrease in consistency with age, but only when individuals tapped with musical  
3 sequences and not with a metronome. Lastly, we found that consistency and asynchrony were  
4 differently modulated by tempo changes depending on the tempo and the type of auditory  
5 sequences. Before discussing these results in depth, it is worth noting that participants' mean  
6 spontaneous motor tempo of 715 ms is close to what has previously been found in older adults  
7 [21,25]. More importantly, it was squarely in between the two stimulus tempi in the paced  
8 tapping task (674 ms and 741 ms). It is therefore reasonable to assume that both tempi were in  
9 the range of comfortable rates for our participants.

### 10 *Effect of NCD severity on consistency*

11 The observed association between MMSE score and tapping consistency is in line with previous  
12 findings. A recent study by Hobeika et al [35] also found reduced consistency in people with  
13 major NCD compared to those with mild or no NCD, as well as a negative linear relationship  
14 between MMSE and consistency during an audio-visual tapping task. However, the latter result  
15 was limited to the metronome condition, whereas participants were not impaired with music.  
16 Interestingly, in our study, cognitive impairment had a global impact on consistency, affecting  
17 tapping with both metronome and music. Perhaps these differences stem from the fact that our  
18 study, which included trials with tempo changes, was more sensitive to uncovering NCD-  
19 related effects. On the other hand, the effect of NCD severity on tapping to music present here  
20 but absent in Hobeika et al.'s study might be attributed to music-induced reward. The  
21 motivating and rewarding qualities of music may boost synchronisation, resulting in more  
22 consistent tapping [65]. Perhaps Hobeika et al.'s stimuli, with original music recordings and  
23 sung lyrics, were more rewarding than our MIDI-based stimuli which did not contain lyrics and  
24 which were also repeated more often within the same experiment. Perhaps a difficulty in  
25 synchronising to music was offset by enhanced synchronicity related to reward In Hobeika et

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1 al.'s study, underscoring the relevance of selecting music for its motivating and rewarding  
2 qualities.

3 The finding of an NCD-related deficit in SMS at a comfortable rate is novel: Some studies have  
4 previously shown lower tapping consistency in people with NCD, but only when they had to  
5 continue tapping after an external sequence had ended [22,32] and/or when the tempo they  
6 synchronised with was far from their comfortable tempo (i.e., slower [22,34] or faster [33]. We  
7 hypothesised that the tempo-changing manipulation would be particularly difficult for more  
8 cognitively impaired people and that MMSE and tempo stability would therefore interact, but  
9 this effect was not observed in this study. It may be that the current task and its analysis pipeline,  
10 examining consistency by 15-second segments, and comparing these segments across  
11 conditions, may have been too crude, given that people only take a few taps to adapt to a new  
12 tempo [18,66,67], at least healthy participants. Additionally, it is possible that the bimodal  
13 nature of the task (audio and video) made the task easier, offsetting the difficulty introduced by  
14 the tempo changes. Finally, while MMSE was chosen as a predictor variable to capture the full  
15 spectrum of cognitive impairment, this may have resulted in reduced statistical power to detect  
16 effects, especially interaction effects, than sampling two extreme groups [68]. Additional  
17 research on rhythmic synchronisation with tempo changes is warranted, as it may provide  
18 insights into how individuals generally entrain to regularities and adapt to changes in their  
19 sensory environment.

20 This study, along with another recent study [35], highlights a global deficit in SMS abilities  
21 among individuals with NCD. Given the established connection between rhythmic and  
22 cognitive abilities, it can be speculated that rhythmic training may confer cognitive benefits.  
23 However, the direct transfer of benefits from musical to non-musical domains requires further  
24 investigation. There exist other neurological conditions like Parkinson's disease, Huntington's  
25 disease, autism spectrum disorder, attention deficit hyperactivity disorder, and dyslexia, where

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1 rhythmic deficits are prominent and rhythm-based training may offer advantages beyond the  
2 motor realm, such as on communication and executive functions [69–75]. By continuing to  
3 study SMS and its links with cognitive abilities, we may get a clearer picture of what processes  
4 may inadvertently be stimulated through rhythm-based interventions, to slow down symptoms  
5 in NCD, but also as a preventive strategy in healthy older adults [76–79]. Finally, the current  
6 results also suggest that sensorimotor problems could serve as a potential diagnostic marker of  
7 NCD, warranting inclusion in the neuropsychological evaluation process, but only as  
8 complementary tests among measures of working memory and attention, for which the link  
9 with NCD is more established.

### 10 *Interaction between audio and age on consistency*

11 Another noteworthy result was an interaction effect of audio and age on consistency. Age  
12 negatively affected tapping consistency when people synchronised their taps with music, but  
13 not with a metronome. This observation offers a more nuanced perspective on past research that  
14 found higher consistency when tapping with metronomes compared to music [12–14] and  
15 research on the effect of age on SMS which often found null results at least with a comfortable  
16 tempo, but which rarely used music material as a stimulus, but rather metronomes (Bangert &  
17 Balota, 2012; Carment et al., 2018; Drewing et al., 2006; Ducheck et al., 1994; Krampe et al.,  
18 2005; McAuley et al., 2006; Turgeon et al., 2011; Vanneste et al., 2001; but see Nagasaki et al.,  
19 1988; Thompson et al., 2015). The current findings, revealing distinct effects of age on tapping  
20 to metronomes versus tapping to music, suggest that beat maintenance and beat induction may  
21 be affected differently. Perhaps older adults experience greater impairment in beat induction  
22 processes, which are crucial for tapping with music, whereas they retain their ability in the  
23 implicit and mechanical aspects of beat maintenance, resulting in comparable performance to  
24 younger individuals when tapping with a metronome.

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1 Previous research indicates that during movement performance in older adults, additional brain  
2 regions, specifically prefrontal areas, become active [82–84], even in situations where there are  
3 no age-related differences in performance outcomes. This suggests increased cognitive control  
4 in executing movements in older individuals. Thus, there might be a beginning decline in motor  
5 control associated with aging, which people compensate for by employing extra neural and  
6 cognitive resources, leading them to achieve performance levels comparable to those of  
7 younger individuals when the task is simple, such as metronome tapping in this study. However,  
8 in tasks that demand higher-level representations and/or executive control such as bimanual  
9 [85–88] and sequential [89] tapping, or having to rapidly extract the beat from a musical  
10 sequence such as in this study, these compensatory mechanisms might not be sufficient, leading  
11 to age-related differences in performance in these more complex tasks. The global effect of  
12 MMSE on consistency discussed in the previous section may also imply that people with NCD  
13 do not engage in compensatory mechanisms as efficiently as healthy older adults, or that this  
14 compensation is not sufficient to mask differences in performance even on simpler tasks like  
15 tapping with a metronome. For future research, it is crucial to use stimuli with varying levels  
16 of complexity, as in this study, to discern the factors that yield observable performance  
17 differences.

### 18 *Interactions between audio, tempo, and tempo stability on consistency, and on asynchrony*

19 With regards to consistency, a three-way interaction emerged. Besides the expected decrease in  
20 consistency following tempo changes and the lower consistency observed with music compared  
21 to metronomes, we noted that consistency was affected by tempo only in one specific  
22 circumstance. Specifically, if the auditory stimulus was a metronome with a shifting tempo,  
23 consistency was higher when the tempo was slow (i.e., following a deceleration) than when it  
24 was fast (i.e., following an acceleration). This complements existing literature which has  
25 reported decelerations as being easier to detect [18] and more easily adapted to [90–93].

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1 Regarding asynchrony, we replicated one of the most stable findings in the SMS literature, the  
2 mean negative asynchrony [5,8,12,13,16,50,94]: Regarding the trials in which the tempo was  
3 stable, patients' taps preceded the beats by several tens of milliseconds when synchronising  
4 with a metronome, whereas they tended to tap close to the beat when tapping with music. In  
5 trials following a tempo change, we would expect taps to be late after an acceleration and  
6 anticipated after a deceleration, relatively to the value of asynchrony in the corresponding stable  
7 condition, at least for a few taps [95,96]. Our results confirm this response pattern in the musical  
8 trials, and after the deceleration of a metronomic tempo. However, after an acceleration with a  
9 metronome, asynchrony remains negative and indeed close to the asynchrony during a fast  
10 stable tempo. This pattern may indicate that people adapt more quickly or efficiently to  
11 accelerating than decelerating metronomes, which would be in contrast to the result we observe  
12 for consistency. However, it may also be that a deceleration is indeed more easily perceived, as  
13 in past studies, but accompanied by an overcorrection response, leading to the large observed  
14 negative asynchrony. Finally, since only one piece of music was used in this study, the observed  
15 asymmetry may also arise from idiosyncrasies specific to this particular piece, especially  
16 considering that the original song contains considerable tempo changes that may have  
17 influenced participants' expectations of the temporal structure.

### 18 *Implications for music-based interventions*

19 The results highlight that motor and cognitive skills may be tightly linked, indicating the  
20 potential of rhythm-based interventions to stimulate non-motor domains, such as working  
21 memory, executive functions, language, and socio-emotional functioning, presenting a  
22 promising avenue for improving the quality of life in individuals with NCDs. The current  
23 findings are relevant to how interventions may be tailored to a person's cognitive status.  
24 Considering that individuals with lower cognitive functioning may have difficulties in  
25 synchronising movements to auditory stimuli, particularly those that are not intrinsically

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1 motivating or rewarding, it is essential to adapt music-based interventions based on cognitive  
2 ability and carefully select appropriate stimuli. One may consider using stable and predictable  
3 beats, potentially including metronomes or music with high beat clarity when working with  
4 older adults, given the age-related decline in beat induction demonstrated here. The observed  
5 reduction in consistency when introducing tempo changes could serve as an argument for  
6 adaptive programmes, starting with simpler, stable tempi and gradually introducing more  
7 complex rhythms to ensure task engagement and build rhythmic skills progressively. While  
8 our research and its implications for rhythm-based interventions are focused on simple,  
9 unimanual tapping, it is essential to note that music-based interventions requiring finer motor  
10 control may specifically engender cognitive benefits [97]. While this study did not compare  
11 audio-visual stimuli with purely auditory stimuli, the high levels of performance observed  
12 here suggest that visual cues of any kind may enhance synchronisation. Finally, non-musical  
13 cognitive training could be intertwined with musical exercises, mutually enhancing each  
14 other's effectiveness.

### 15 *Limitations*

16 Our sample included individuals with NCD of diverse origins, predominantly AD, vascular  
17 NCD, and NCD of mixed aetiology. While this sample is likely representative of the general  
18 population of individuals with NCD, the limited numbers within each subgroup did not allow  
19 us to explore differences between various aetiologies, which presents an interesting avenue for  
20 future research. In fact, we are aware of only one study [34] that compared sensorimotor  
21 synchronisation abilities across different NCD groups and identified differences between AD  
22 and frontotemporal NCD.

23 We recognised the importance of good hearing and vision for our experiment, screening out  
24 potential participants with impairments or those who did not have the necessary aids with them.  
25 However, we did not conduct formal audiometry or visual acuity tests, leaving the possibility



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1 that performance variations could be attributed in part to differences in hearing and visual  
2 abilities, considering the common prevalence of hearing loss [98] and visual impairment  
3 [99,100] in older adults.

4 It is worth repeating that we deliberately chose to use audio-visual stimuli to synchronise to, a  
5 manipulation deemed necessary to maintain participants' engagement and motivation  
6 throughout the task. Nevertheless, this prevented us from assessing the degree to which  
7 participants relied on auditory versus visual information, or how performance might be affected  
8 if individuals had access to information from only one modality, which presents an interesting  
9 direction for future investigation.

### 10 *Concluding remarks*

11 This study highlights two primary findings. The first is an influence of MMSE score on tapping  
12 consistency, irrespective of audio stimulus type and of the presence or absence of tempo  
13 changes, suggesting an effect of NCD severity on the ability to maintain a steady rhythm. Two  
14 possible mechanisms could explain this, which are not mutually exclusive. Firstly, neural  
15 reorganising over the course of the disorder may increasingly engage non-motor areas to sustain  
16 performance during a simple motor task, indicating a shift towards more cognitive and effortful  
17 processing of rhythm. Secondly, even simple metronome tapping may require some degree of  
18 attention and working memory, albeit less than tapping with music. Healthy ageing individuals  
19 may therefore maintain a consistent level of performance when tapping with a metronome,  
20 whereas in more cognitively impaired individuals with a lower MMSE, the impairment of  
21 attention and working memory is severe enough to significantly hinder performance, even in  
22 tapping with a simple metronome, arguably the simplest form of SMS. However, it is important  
23 to acknowledge the importance of tempo changes in half of the trials. While the statistical  
24 analysis indicates that the impact of cognitive impairment held for both conditions (with and  
25 without tempo changes), it may still be that the primary difficulty in this study might have arisen

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1 from the presence of tempo changes in half of the trials, even though the difference in decline  
2 of consistency as a function of MMSE across the two levels of tempo stability was not large  
3 enough to yield statistical significance. Although we did not observe an interaction between  
4 tempo stability and MMSE in this study, the current results do not eliminate the possibility that  
5 individuals with NCD might experience specific difficulties in adapting to tempo changes. The  
6 involvement of working memory, attention, and cognitive flexibility in error correction could  
7 still play a role, warranting further investigation. The second result shows an age-related decline  
8 in consistency during SMS but only when tapping with music, whereas consistency remains  
9 stable when tapping with a metronome. This observation implies that beat induction, a process  
10 especially relevant for perceiving the underlying beat in musical sequences, is affected in  
11 healthy ageing, potentially indicating a beginning decline of attention and working memory.  
12 Beat maintenance, on the other hand, may be relatively spared.

13 In conclusion, this research emphasises the importance of sensorimotor impairment as a  
14 symptom in NCD. The findings suggest that motor and cognitive skills may be tightly linked,  
15 implying that deficits in one domain may potentially impact the other. This underplay  
16 underlines the potential for rhythm-based training to inadvertently stimulate non-motor  
17 domains, such as working memory, executive functions, language, and socio-emotional  
18 functioning, presenting a promising avenue for enhancing the quality of life in individuals living  
19 with NCDs. These insights provide a foundation for continued research and therapeutic  
20 interventions aimed at enhancing well-being in healthy and pathological ageing by targeting  
21 the sensorimotor domain. The possibility for therapeutic approaches are vast, ranging from  
22 group drumming [101] to remote interventions using mobile devices [102].

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12 During the preparation of this work the authors used the large language model ChatGPT [103]  
13 in order to improve the flow and readability of the writing. After using this tool, the authors  
14 reviewed and edited the content as needed and take full responsibility for the content of the  
15 publication.

### 16 CONFLICT OF INTEREST

17 The authors have no conflict of interest to report.

### 18 DATA AVAILABILITY STATEMENT

19 The data supporting the findings and a script to analyse them are openly available at  
20 [https://osf.io/78k46/?view\\_only=9e15fa4ac33d49e1aff47bd609c305ab](https://osf.io/78k46/?view_only=9e15fa4ac33d49e1aff47bd609c305ab).

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22

## AGEING, NCD, AND BEAT SYNCHRONISATION

### 1 TABLES AND FIGURES

**Table 1**

*Demographic and clinical information of patients*

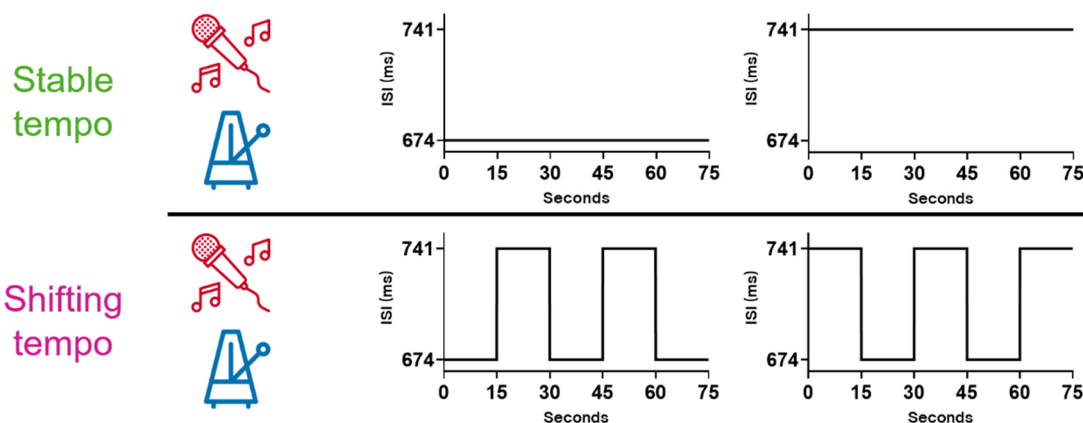
	N	Median [first quartile, third quartile] or frequencies (%)	Range
Age	51	82 [76, 86]	61-92
Gender (women)	51	35 (69%)	
Years of education	51	12 [7, 14]	3-18
Musical expertise (out of 28)	51	3 [2,4]	0-12
Diagnosis	48		
Major NCD			
Minor NCD			
No NCD			
MMSE (out of 30)	51	25 [23, 28]	19-30
ADL (out of 6)	50	5.5 [4.5, 6]	2-6
IADL (out of 4)	50	2 [1, 3]	0-4
GDS (out of 15)	50	5 [3, 8]	1-12
GAI (out of 5)	50	2 [1, 4]	0-5

NCD = neurocognitive disorder; MMSE = Mini-Mental State Examination; ADL = activities of daily living; IADL = instrumental activities of daily living; GDS = Geriatric Depression Scale; GAI = Geriatric Anxiety Inventory

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**Figure 1**

*Types of audio and temporal structures used in the experimental trials*

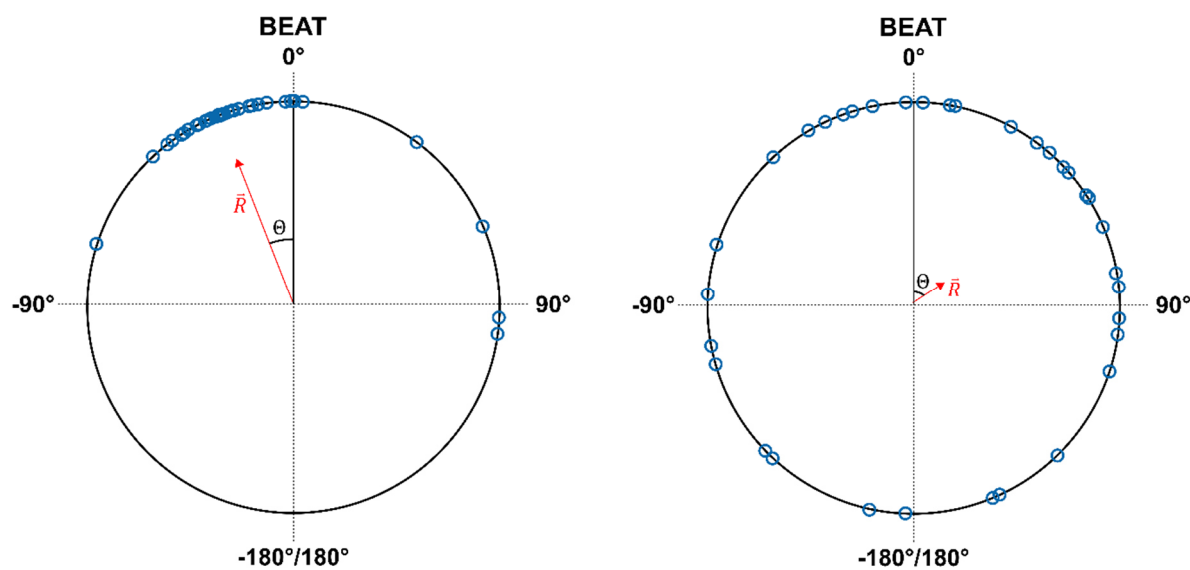


*Note.* Using two types of audio (music and metronome) and tempi corresponding to four temporal patterns (A, stable tempo of 674 ms; B, stable tempo of 741 ms; C, shifting tempo starting at 674 ms; D, shifting tempo starting at 741 ms) resulted in eight different experimental trials.

1

**Figure 2**

*Two examples of circular synchronisation analysis in a given trial*



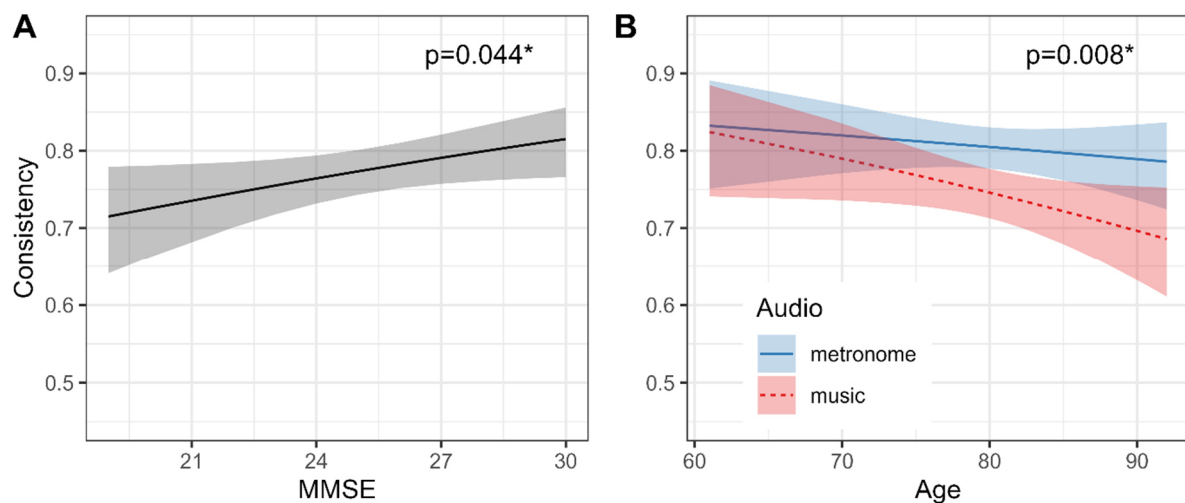
## AGEING, NCD, AND BEAT SYNCHRONISATION

*Note.* Each inter-onset interval is converted to degrees on a circular scale. The time at which each tap occurs, relative to the beat (= 0 degrees) is then represented by a specific angle on the circle (blue minicircles). The mean vector  $\bar{R}$  summarises the performance during a 15-second segment. The mean direction ( $\Theta$ ) represents asynchrony, whereas the length  $\vec{R}$  (going from 0 to 1) represents consistency. (A) Taps occurred on average before the beat (negative asynchrony) and close to each other (high consistency, long vector). (B) Taps occurred on average after the beat (positive asynchrony) but were scattered around the circle (low consistency, short vector).

1

### Figure 3

*Effects of MMSE, and of the interaction of audio and age on consistency*



*Note.* (A) More cognitively impaired people (i.e., with a lower MMSE score) tapped with a lower level of consistency. (B) Consistency decreased with age, but only in the music conditions.

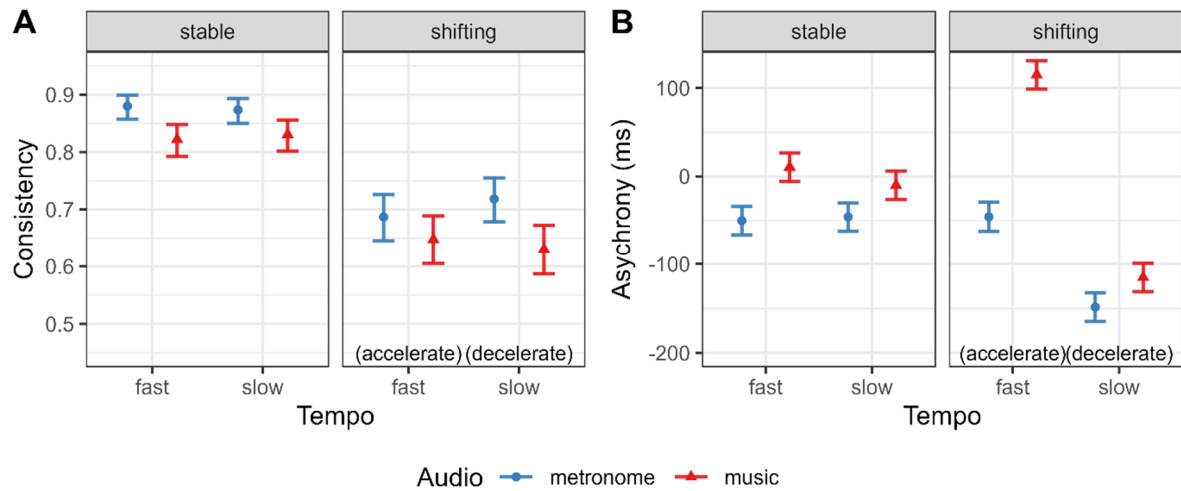
MMSE, Mini-Mental State Examination

2

### Figure 4

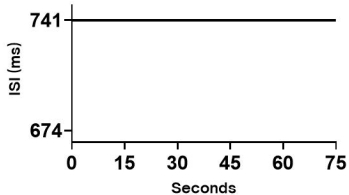
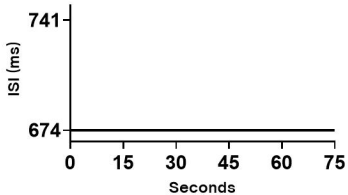
## AGEING, NCD, AND BEAT SYNCHRONISATION

*Effects of audio, tempo, and tempo stability on consistency ( $p = .107$ ; A) and asynchrony ( $p < .001$ ; B)*

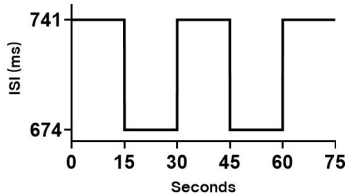
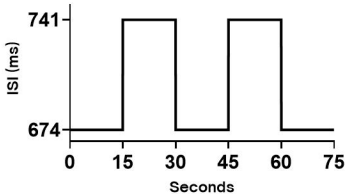


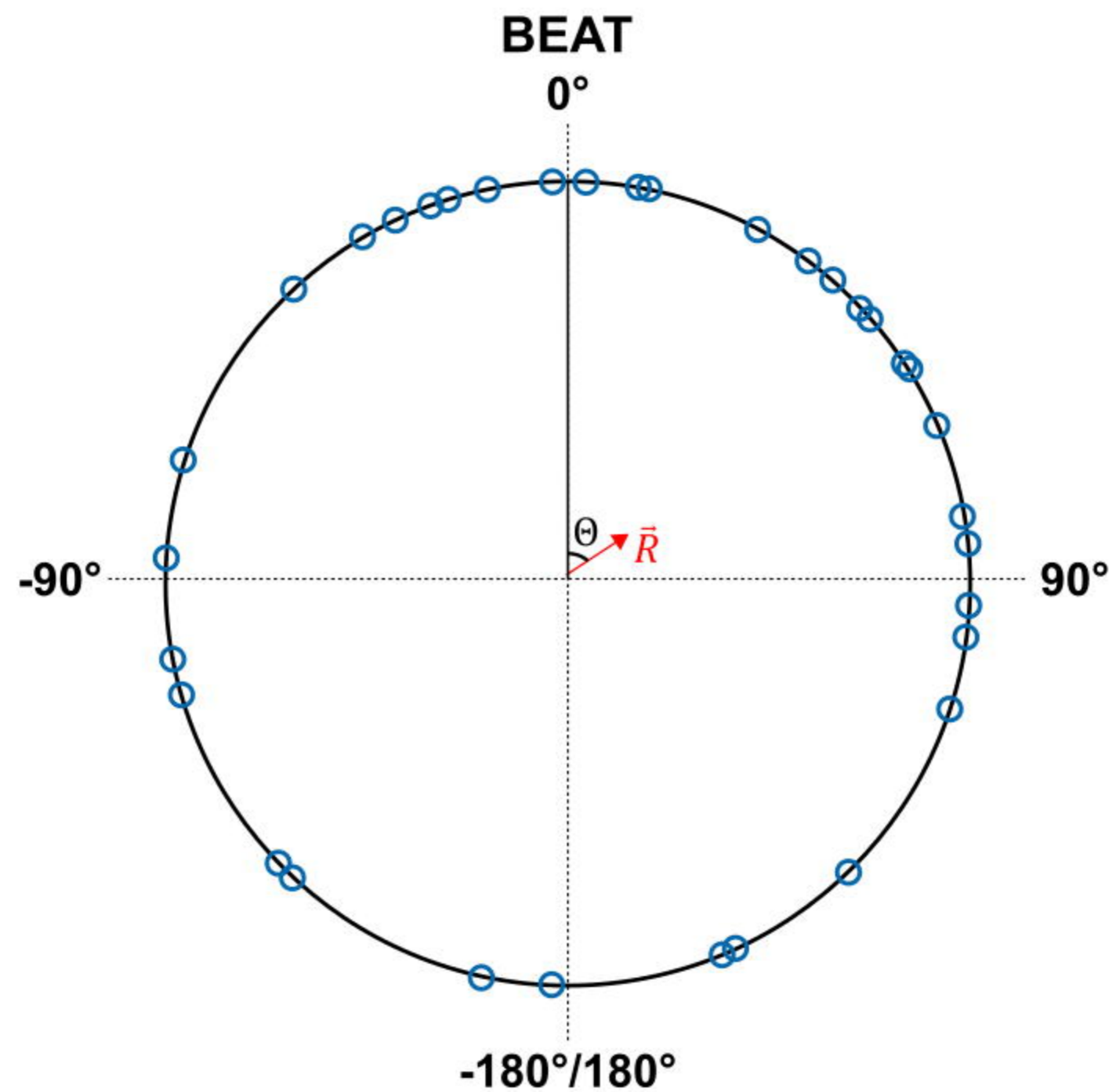
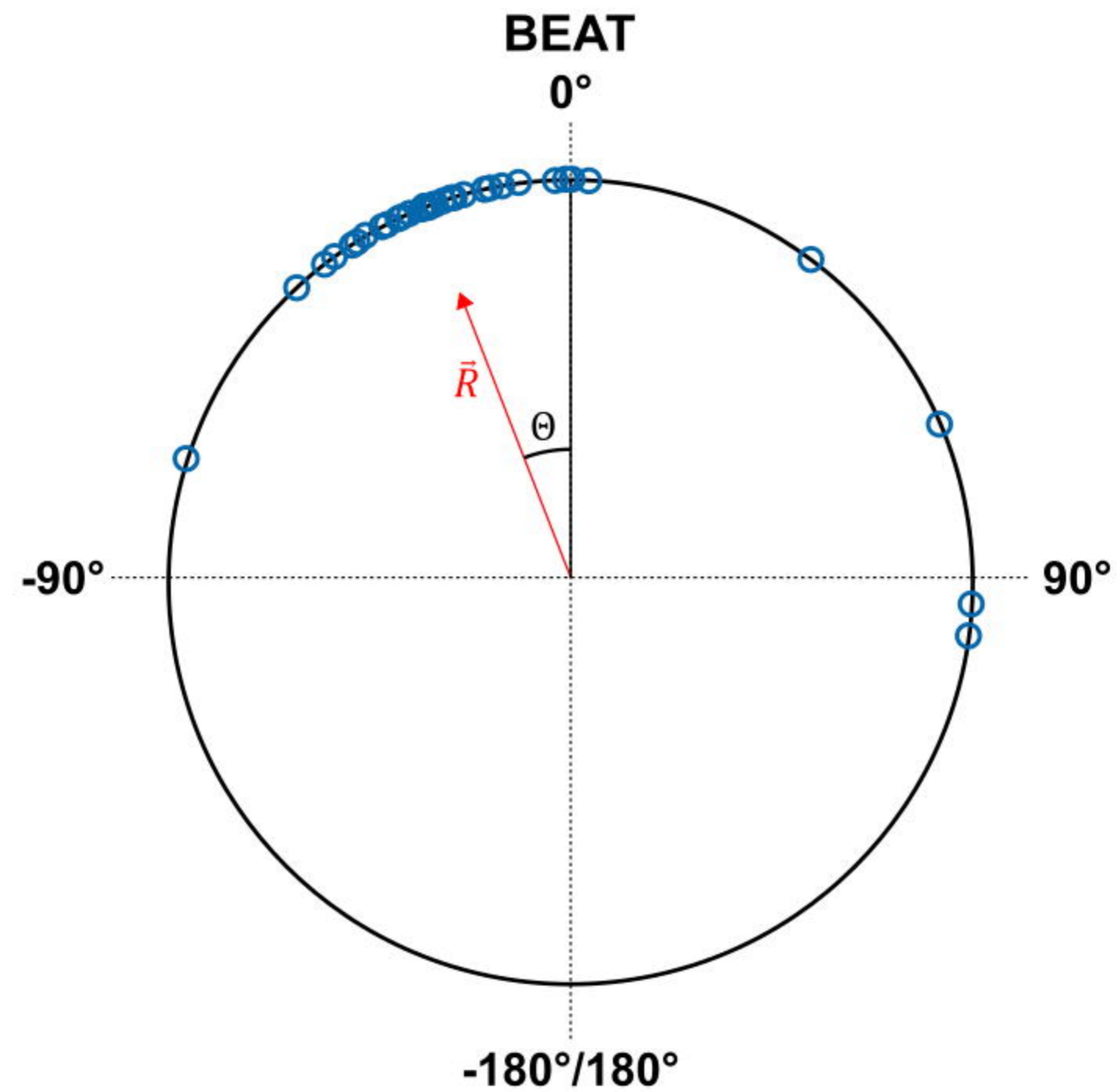
*Note.* In order to fulfil the assumption of multivariate normality, the dependent variable asynchrony was transformed by taking the cubic root of its absolute value and multiplying it with its original sign. However, graph B was created by taking estimated marginal means and standard deviations of a linear mixed model with non-transformed data.

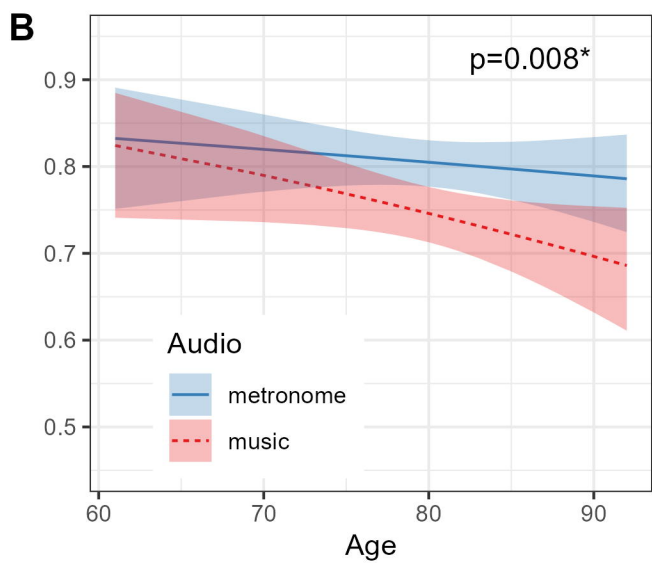
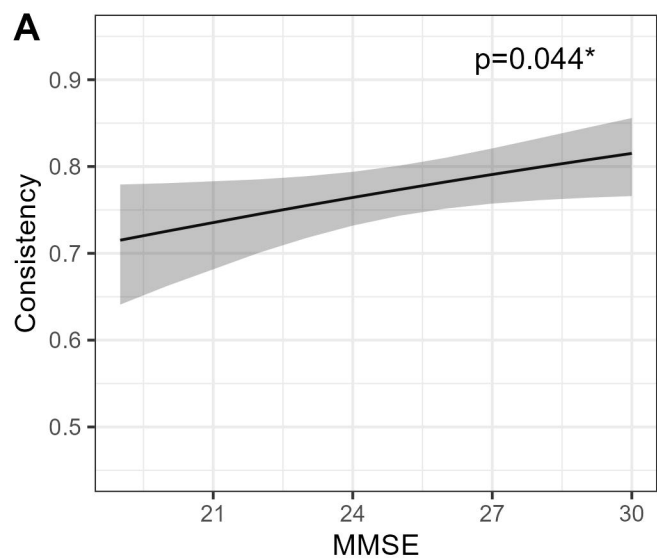
Stable tempo



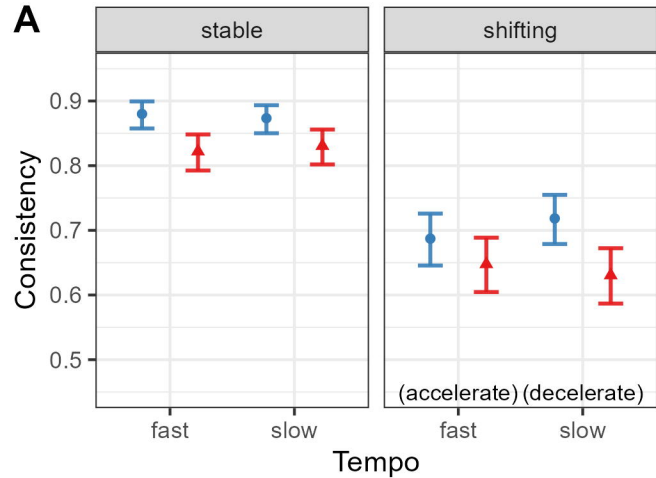
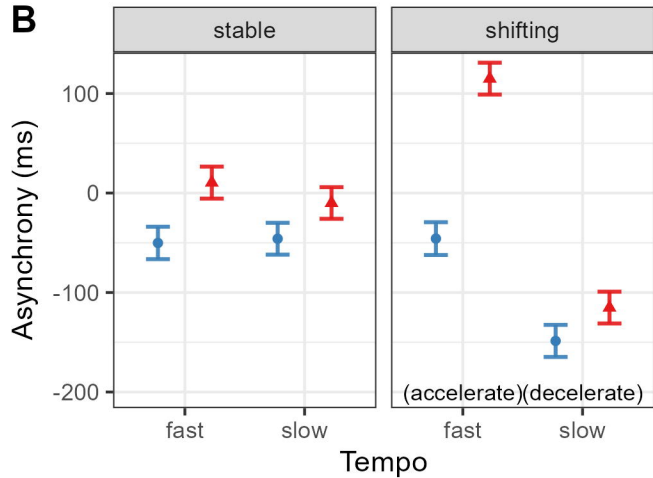
Shifting tempo









**A****B**

Audio ● metronome ▲ music