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Musical rhythm and synchronization in normal and pathological aging

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Pearl

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Abstract

Across the globe and across the lifespan, music engages in us an urge to move. Central to this phenomenon is sensorimotor synchronization (SMS), the process of coordinating movement with rhythmic sensory stimuli, such as music or a metronome. SMS is critical not only for keeping the beat when moving with music, but also in a variety of interpersonal interactions. Attending to temporal regularities in the environment facilitates event prediction, a fundamental aspect of numerous cognitive and social operations.

Given the global population aging, it is increasingly important to understand the role of aging and neurocognitive disorders (NCDs), such as Alzheimer's disease, in SMS, to determine how it is affected and how it might be stimulated. This thesis focuses on elucidating the mechanisms that influence how older adults move in synchrony with external rhythms.

We conducted a literature review (**Chapter 2**) and four successive studies to investigate SMS in healthy and pathological aging. Each study used the same hand-tapping task with metronomic and musical sequences, manipulating only the rhythmic sequences to address specific research questions. All participants were recruited at the same geriatric day hospital, except for those the study described in **Chapter 5**, which included healthy older and younger adults.

In **Chapter 4** (n = 51), we report that global cognitive function is associated with tapping performance, and age is associated with performance when tapping to

music. In **Chapter 5** (*n* = 88), we found that in healthy elderly participants who were slightly younger, tapping performance was not associated with age, but musical expertise affected synchronization. **Chapter 6** (*n* = 177) demonstrates that short-term memory and inhibition capacities are related to synchronization to music. In the final experiment (*n* = 84), we show that as the saliency of a beat decreases, reliance on inhibition, beat perception, and motor variability increases (**Chapters 7**).

Age-related and NCD-related declines in SMS may stem from changes in cognitive abilities and motor function. The demonstrated connections between cognitive abilities and rhythmic skills highlight the potential for music-based interventions that incorporate rhythmic synchronization to stimulate cognitive functions. Such tailored interventions, when employed successfully, may not only improve a person's sense of rhythm, but rehabilitate cognitive function in individuals with NCD, protect healthy older adults from cognitive decline, and improve overall well-being and quality of life of older adults.

Keywords: music; memory; communication; aging; neuropsychology

Résumé en français

Partout dans le monde et tout au long de la vie, la musique nous incite à bouger. Au cœur de ce phénomène se trouve la synchronisation sensorimotrice (SSM). Il s'agit d'un processus de coordination des mouvements avec les stimuli sensoriels rythmiques, tels que la musique ou le métronome. La SSM est essentielle non seulement pour garder le rythme lorsque l'on bouge avec de la musique, mais aussi dans diverses interactions interpersonnelles. La prise en compte de ces régularités temporelles dans l'environnement facilite la prédiction d'événements, un aspect fondamental de nombreuses opérations cognitives et sociales.

Compte tenu du vieillissement de la population mondiale, il est de plus en plus important de comprendre le rôle du vieillissement et des troubles neurocognitifs liés aux pathologies neurodégénératives, telle que la maladie d'Alzheimer, sur la SSM, afin de déterminer comment cette aptitude sensori-motrice est affectée et comment elle pourrait être stimulée. Cette thèse se concentre sur la recherche des mécanismes qui influencent la façon dont les personnes âgées bougent en synchronisation avec les rythmes externes.

Après une revue de littérature (**Chapitre 2**), nous avons mené quatre études successives en utilisant des tâches de tapping manuel avec une séquence métronomique ou musicale afin d'étudier la SSM dans le vieillissement normal et pathologique. Chaque étude a utilisé la même tâche qui consiste à taper avec la main (tache de tapping) en rythme avec le battement d'une séquence

métronomique ou musicale. Les séquences rythmiques ont été manipulées pour répondre à des questions de recherche spécifiques. Tous les participants ont été recrutés dans le même hôpital de jour gériatrique, à l'exception de ceux·elles de l'étude décrite au **Chapitre 5**, qui comprenait des adultes jeunes et âgés en bonne santé.

Dans le **Chapitre 4** (*n* = 51), nos résultats ont montré que la fonction cognitive globale est associée à la performance de tapping, et que l'âge est associé à la performance de tapping en musique. Dans le **Chapitre 5** (*n* = 88), nous avons constaté que chez les participant·e·s âgé·e·s en bonne santé qui étaient légèrement plus jeunes, la performance de tapping n'était pas associée à l'âge. En revanche, l'expertise musicale affectait la synchronisation. Le **Chapitre 6** (*n* = 177) a mis en évidence que la mémoire à court terme et les capacités d'inhibition sont liées à la synchronisation musicale. Dans la dernière expérience (**Chapitre 7** ; *n* = 84), nous montrons qu'à mesure que la saillance d'un rythme diminue, la dépendance à l'égard de l'inhibition, de la perception du rythme et de la variabilité motrice augmente.

Le déclin de la SSM lié à l'âge et aux pathologies neurodégénératives peut découler de changements dans les fonctions cognitives et motrices. Les liens démontrés entre les capacités cognitives et les aptitudes rythmiques soulignent le potentiel des interventions musicales qui intègrent la synchronisation rythmique pour stimuler les fonctions cognitives. Ces interventions basées sur le rythme musical, lorsqu'elles sont utilisées avec succès, peuvent non seulement améliorer le sens du rythme d'une personne, mais pourraient aussi réhabiliter

certaines fonctions cognitives chez les personnes atteintes de maladie neurodégénératives, voire même protéger les personnes âgées en bonne santé contre le déclin cognitif et améliorer le bien-être général et la qualité de la vie des personnes âgées.

Mots-clés: musique; mémoire; communication; vieillissement;

neuropsychologie

Thesis summary for the general public

Across the lifespan, music makes us want to move. This coordination, termed sensorimotor synchronization, is central to many social and cognitive functions. As the world's population ages, understanding how aging and neurocognitive disorders, such as Alzheimer's disease, affect SMS is vital. This thesis explores how older adults move in synchrony with external rhythms. In four experiments, I show that age, global cognitive function, and particularly short-term memory, and inhibition, impact rhythmic skills. Understanding these mechanisms should inform the development of music-based interventions that could improve certain cognitive functions as well as enhance quality of life for older adults.

Résumé de thèse vulgarisé pour le grand public

Tout au long de la vie, la musique nous donne envie de bouger. Cette coordination, appelée synchronisation sensorimotrice, est au cœur de nombreuses fonctions sociales et cognitives. La population mondiale vieillissant, il est essentiel de comprendre comment le vieillissement et les troubles neurocognitifs, tels que la maladie d'Alzheimer, affectent la synchronisation sensorimotrice. Cette thèse explore la manière dont les personnes âgées bougent en synchronisation avec les rythmes externes. Dans quatre expériences, je montre que l'âge, le fonctionnement cognitif global, et notamment la mémoire à court terme et l'inhibition, ont un impact sur les compétences rythmiques. Comprendre ces relations devrait permettre de développer des interventions basées sur la musique qui pourraient améliorer certaines fonctions cognitives et améliorer ainsi la qualité de vie des personnes âgées.

Résumé détaillé (en français)

Introduction

Cette thèse de doctorat étudie les mécanismes qui sous-tendent la capacité des personnes âgées à synchroniser leurs mouvements avec des rythmes externes, avec des implications pour la rééducation et l'amélioration de la qualité de vie, en particulier chez les personnes souffrant de troubles neurocognitifs, tels que la maladie d'Alzheimer, la démence vasculaire et la démence fronto-temporale. Avec le vieillissement de la population mondiale et l'augmentation de la prévalence des maladies neurocognitives, il est essentiel de comprendre la synchronisation sensorimotrice (SSM) dans ce groupe de personnes. La synchronisation sensorimotrice, qui se définit comme le fait de bouger au rythme de la musique, est un comportement universel et spontané qui se manifeste dès le plus jeune âge et persiste jusqu'à la fin de l'âge adulte. Il permet la coordination avec des événements rythmiques et est essentiel pour les interactions interpersonnelles. Les activités musicales ont démontré des avantages cognitifs, émotionnels et sociaux pour les personnes atteintes de troubles neurocognitifs (NCD), comme l'ont montré des essais contrôlés randomisés. Cette thèse cherche à savoir si le rythme et la stimulation de la SSM font partie intégrante de ces bénéfices, en se concentrant sur les capacités cognitives et la SSM chez des populations vieillissantes présentant différents niveaux de déficience cognitive.

Revue de la littérature

La SSM consiste à coordonner les mouvements avec des stimuli rythmiques, tels que la musique ou les métronomes. Elle englobe la perception du rythme (extraire et suivre un rythme à partir de modèles rythmiques), la production motrice (créer des mouvements rythmiques) et l'harmonisation auditivo-motrice (intégrer la perception du rythme aux réponses motrices). Un autre élément de la SSM est la correction des erreurs, qui permet aux individus de s'adapter aux changements de tempo – un processus lié à la flexibilité cognitive et à la mémoire de travail, des capacités qui sont souvent compromises chez les personnes atteintes d'une maladie neurodégénérative. La SSM repose sur des fonctions cognitives telles que l'attention, comme propose la Dynamic Attending Theory, qui suggère que l'attention oscille avec les rythmes auditifs, améliorant ainsi la prédiction d'événements futurs.

Alors que la littérature suggère que la SSM avec des sons isochrones simples est relativement préservée chez les personnes âgées en bonne santé, la performance lors de l'écoute de musique pourrait diminuer avec l'âge, en particulier à des tempi plus lents et avec une charge cognitive plus importante. Les personnes âgées, en particulier celles qui souffrent d'une maladie neurodégénérative modérée à sévère, peuvent en outre avoir des difficultés avec les paradigmes de continuation. Par ailleurs, la recherche indique que le tempo moteur spontané ralentit après l'âge de 75 ans environ, ce qui met en évidence les problèmes moteurs et cognitifs liés à l'âge. La SSM pourrait être influencée par des capacités cognitives telles que l'attention, la mémoire de travail et l'inhibition. Ces relations sont illustrées par les performances observées dans d'autres populations. Par exemple, les enfants et les adultes atteints de Trouble déficit de l'attention avec ou sans hyperactivité présentent des troubles de la synchronisation rythmique. En outre, l'expertise musicale joue un rôle dans la SSM. Il a été démontré qu'une formation musicale précoce améliore la synchronisation rythmique et la mémoire de travail auditive. Une plus grande expertise musicale est associée à de meilleures performances en SSM. La charge cognitive est également importante. En particulier dans les conditions qui exigent l'adaptation ou la continuation des rythmes, la SSM pourrait être de plus en plus compromise chez les personnes atteintes d'une maladie neurodégénérative.

Si les études mettent en évidence l'impact de l'âge et des troubles cognitifs sur la SSM, les recherches sur les populations atteintes de NCD modérées ou sévères sont limitées. Aussi, notons qu'il existe peu d'études portant sur la SSM en présence de signaux auditifs complexes (par exemple, de la musique plutôt que des métronomes). Des recherches devraient être menées sur des groupes d'âge et des profils cognitifs plus variés.

Méthodologie

Quatre études ont été menées sur la SSM chez les personnes âgées en utilisant des tâches de tapping de la main sur une table avec un capteur de force, où les participant·e·s synchronisaient leur mouvement de tapping avec de la musique et des métronomes.

Plus de 300 participant·e·s, pour la plupart des personnes âgées, ont été recruté·e·s, y compris des personnes en bonne santé et d'autres présentant des déficiences cognitives plus ou moins importantes. Les données relatives au tapping ont été calculées à l'aide de statistiques circulaires et des modèles à effets mixtes ont été utilisés pour l'analyse, en tenant compte des facteurs démographiques.

Les participant·e·s ont été recruté·e·s principalement dans un hôpital de jour gériatrique, à l'exception d'une étude qui incluait des jeunes et des adultes plus âgés en bonne santé. Les capacités cognitives ont été évaluées à l'aide de la Mini-Mental State Examination (MMSE), de tests de mémoire à court terme et de travail (Digit Span forward et backward, respectivement) et d'inhibition (tests de Stroop et Go/No-go). L'expertise musicale a été évaluée à l'aide d'une version du Goldsmiths Musical Sophistication Index (Gold-MSI).

Les stimuli comprenaient des métronomes et des stimuli musicaux avec des intervalles inter-stimulus de 600-800 ms. Dans certains essais de l'une des études, les participant·e·s se sont synchronisé·e·s avec un musicien en direct plutôt qu'avec un enregistrement vidéo. Dans deux autres études, la synchronisation s'est faite uniquement avec des stimuli vidéos, tandis que dans les derniers stimuli, les stimuli étaient uniquement auditifs, sans apport visuel. Dans toutes les études, la constance et l'asynchronie de la synchronisation ont été analysées. Dans la dernière étude décrite ici, le Beat Alignment Test a également été utilisé pour évaluer la perception des battements, et une mesure de tapping spontané a été utilisée pour mesurer la production pure de battements.

Constatations et résultats

Étude 1

- L'introduction de changements de tempo a réduit la cohérence du tapping, avec de moins bonnes performances lors de la synchronisation avec la musique qu'avec les métronomes.
- Les scores MMSE les plus bas (indiquant une plus grande déficience cognitive) sont corrélés à une moins bonne synchronisation. L'âge a eu un impact spécifique sur la cohérence de la synchronisation avec la musique.
- L'asynchronie du tapping était plus importante (plus négative) avec la musique qu'avec les métronomes.

Étude 2

- Chez les personnes âgées en bonne santé, l'expertise musicale a amélioré la constance de la synchronisation. Les participants tapaient généralement en avance sur les battements du métronome, les plus jeunes et les moins expérimenté·e·s musicalement montrant une plus grande asynchronie avec la musique.

- La synchronisation était plus constante avec les métronomes et diminuait lors des changements de tempo, quel que soit l'âge.

Étude 3

- D'une manière générale, la synchronisation est moins constante lorsque l'on tape avec de la musique. En outre, la cohérence était moins bonne avec un musicien en direct qu'avec un enregistrement vidéo.
- La synchronisation avec le métronome a été influencée par l'était cognitif (scores MMSE), tandis que l'âge a affecté la synchronisation avec la musique. La mémoire à court terme et l'inhibition ont également eu un impact sur la constance de la synchronisation avec la musique.

Étude 4

- Une faible saillance du rythme augmente la dépendance à l'égard de l'inhibition et de la variabilité motrice. La saillance du rythme interagit en outre avec les capacités cognitives telles que la mémoire à court terme et l'inhibition.

Discussion

Le déclin de la SSM semble être plus prononcé au cours des dernières décennies de la vie et chez les populations cognitivement vulnérables. L'une des principales conclusions de l'étude est que les scores à la MMSE ont un impact sur la synchronisation, peut-être davantage lorsque l'on tape avec des métronomes. En revanche, la synchronisation avec la musique fait davantage appel aux ressources cognitives, notamment à la mémoire à court terme et à l'inhibition. L'asynchronie négative, qui est généralement observée avec les métronomes, peut également apparaître lors de la synchronisation avec la musique, où elle est sensible à l'âge et à l'expertise musicale. Un résultat à retenir de cette recherche est l'importance de la saillance du rythme. Une faible saillance du rythme nécessite un effort cognitif plus important, ce qui souligne l'importance des processus cognitifs dans l'extraction d'un rythme à partir de la musique.

Ces résultats suggèrent que la synchronisation par métronome est plus automatique, alors que la synchronisation par la musique implique un traitement cognitif plus complexe. Les interventions musicales intégrant la synchronisation rythmique pourraient stimuler ou réhabiliter les fonctions cognitives chez les personnes atteintes de maladies neurodégénératives et prévenir le déclin cognitif chez les personnes âgées en bonne santé.

Conclusion

Cette recherche doctorale démontre la relation entre les capacités cognitives et la synchronisation rythmique. Cela suggère que la musique peut avoir un potentiel d'intervention thérapeutique dans le vieillissement et dans les soins aux personnes atteintes des NCD. Les programmes basés sur le rythme pourraient améliorer les fonctions sensorimotrices, atténuer le déclin cognitif et améliorer le bien-être des personnes âgées. Les recherches futures devraient explorer la SMM dans diverses étiologies de NCD et divers niveaux de gravité, ainsi que les effets de différents niveaux de complexité musicale. En outre, des essais contrôlés randomisés devraient être menés pour évaluer l'efficacité des interventions rythmiques sur la rééducation cognitive. Enfin, des études de neuro-imagerie pourraient être mises en place pour étudier les changements cérébraux associés à l'entraînement de la SSM. Cette thèse jette les bases du développement d'interventions rythmiques adaptées à des profils cognitifs spécifiques, afin d'améliorer la qualité de vie des populations vieillissantes.

Dissemination of research output

Journal publications

von Schnehen, A., Hobeika, L., Huvent-Grelle, D., & Samson, S. (2022). Sensorimotor synchronization in healthy aging and neurocognitive disorders. *Frontiers in Psychology*, *13*, Article 838511.

von Schnehen, A., Hobeika, L., Houot, M., Recher, A., Puisieux, F., Huvent-Grelle, D., & Samson, S. (2024). Sensorimotor Impairment in Aging and Neurocognitive Disorders: Beat Synchronization and Adaptation to Tempo Changes. *Journal of Alzheimer's Disease*, *100*(3), 945-959.

von Schnehen, A., Hobeika, L., Ghilain, M., Poirier-Quinot, D., Puisieux, F., Huvent-Grelle, D., & Samson, S. Cognitive processes underlying synchronization to music in older adults with and without neurocognitive disorder. [Manuscript submitted for publication].

Scientific conferences

von Schnehen, A., Hobeika, L., Huvent-Grelle, D., & Samson, S. (2022). *The impact of neurocognitive disorders on sensorimotor synchronization with simple and complex rhythmic sequences*. The 15th International Conference of Students of Systematic Musicology (SysMus22), Ghent, Belgium.
(oral presentation)

von Schnehen, A., Hobeika, L., Huvent-Grelle, D., Puisieux, F., & Samson, S. (2022). *The impact of cognitive functioning on sensorimotor synchronisation with simple and complex rhythmic sequences.* Music & Hearing Health Workshop, Oldenburg, Germany.
(poster presentation)

von Schnehen, A., Hobeika, L., Huvent-Grelle, D., Puisieux, F., & Samson, S. (2023). *The influence of age and cognitive decline on sensorimotor synchronisation in patients with neurocognitive disorders.* The 17th International Conference on Music Perception and Cognition, Tokyo, Japan.
(oral presentation)

von Schnehen, A., Hobeika, L., & Samson, S. (2023). *Tapping into sophistication: how different facets of musicality impact synchronisation.* The 16th International Conference of Students of Systematic Musicology (SysMus23), Sheffield, UK.
(oral presentation)

von Schnehen, A., Foster, N., Puisieux, F., Huvent-Grelle, D., Dalla Bella, S., Hobeika, L., & Samson, S. (2024). *Neurocognitive disorders are associated with impaired beat induction during sensorimotor synchronisation to music.* CRBLM 2024 Symposium "Perspectives on Language and Music", Montreal, Canada.
(poster presentation)

von Schnehen, A. (2024). *Rhythmic abilities and cognitive functioning in aging and neurocognitive disorders.* BRAMS Lecture, Montreal, Canada.
(guest lecture)

von Schnehen, A., Foster, N., Puisieux, F, Huvent-Grelle, D., Dalla Bella., S., Hobeika, L., & Samson, S. (2024). *The impact of age-related cognitive decline on beat perception in music*. 6th CIRMMT-OICRM-BRAMS (COBS) student colloquium, Montreal, Canada.
(poster presentation; best poster presentation award)

von Schnehen, A., Foster, N., Puisieux, F., Huvent-Grelle, D., Dalla Bella, S., Hobeika, L., & Samson, S. (2024). *Age-related cognitive impairment disrupts the ability to extract a beat from music*. The Neurosciences and Music – VIII, Helsinki, Finland.
(poster presentation)

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Chapter 1

Introduction

Music naturally engages in us an urge to move. Moving to music is a propensity that is natural, spontaneous and shared across cultures (Levitin et al., 2018). It emerges without specific training at a very young age (Zentner & Eerola, 2010) and persists into older adulthood (Lesaffre et al., 2017). The perception of temporal regularities in auditory rhythms is central to a wide range of behaviors. The periodicity of musical beats yields optimal predictability of upcoming events, allowing precise coordination of body movement with rhythmic events in time (Nozaradan, 2014).

Coordinating rhythmic movement with an external rhythm - termed sensorimotor synchronization (SMS) in the scientific literature - has been the subject of ample scientific research (Repp, 2005; Repp & Su, 2013). SMS encompasses a wide range of activities, such as moving one's limbs rhythmically, walking, and dancing. It is fundamental for effective communication in interpersonal contexts and serves as a prerequisite for event prediction (Bispham, 2006; Obleser & Kayser, 2019). Conversely, difficulties in perceiving temporal regularities might hamper interpersonal communication and lead to isolation. Therefore, measuring and potentially stimulating SMS is critical, as it not only pertains to musical rhythm but also to the ability to predict events in the environment and relate to others .

SMS involves several interconnected processes, including beat perception, motor production, and the ability to map motor output to a regular external sequence. Beat perception allows individuals to extract a beat from a rhythmic pattern and to follow it, while motor production describes the ability to produce regular rhythmic movement with any body part. Auditory-mapping integrates these processes, enabling precise entrainment of a motor rhythm with an external rhythm (Molinari et al., 2007; Repp, 2006).

There is considerable inter-individual variability in rhythmic abilities (Dalla Bella et al., 2024; Niarchou et al., 2022; Tierney et al., 2017). Different profiles of rhythmic abilities may be associated with distinct cognitive profiles, suggesting that assessing SMS can provide valuable insights into an individual's cognitive functioning (Dalla Bella et al., 2024).

Given the importance of SMS for daily functioning and social interaction, it is crucial to understand how aging affects this ability. Healthy aging may affect sensorimotor function due to changes in sensory, motor, and cognitive processes. Pathological aging, as seen in neurocognitive disorder (NCD), can exacerbate these declines. NCD refers to a group of acquired disorders marked by a progressive decline in cognitive functions, affecting various domains such as memory, attention, language, learning, and social cognition (American Psychiatric Association, 2013). Before the 5th edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), major NCD was referred to as dementia, a term still used by many clinicians. However, I will adhere to DSM-5 nomenclature in this thesis and use the term NCD.

With a global population aging, it becomes increasingly important to understand how aging and NCD impact the ability to synchronize movements with music.

Using movement to music in a therapeutic setting holds promise for enhancing the quality of life and perhaps even to stimulate the cognitive function of older individuals (Alain et al., 2019; Bugos et al., 2007; Marie et al., 2023; Schneider et al., 2019; Seinfeld et al., 2013; Wang et al., 2023) and those with NCD (Choi et al., 2009; Narme et al., 2014; Sherratt et al., 2004). By examining SMS in both healthy older adults and those with NCD, and by examining its relationships with cognitive abilities and musical expertise, I aim to uncover critical insights into the interplay between aging, cognitive decline and the mechanisms that underlie movement to music. This knowledge could inform the development of rhythm-based interventions to support sensorimotor functions and improve the well-being of older adults.

This thesis explores the nuances of SMS in healthy aging and NCD. In the following part (**Chapter 2**), I present a literature review outlining the current state of research pertaining to SMS in healthy aging and NCD. **Chapter 3** concludes the theoretical introduction of this thesis by summarizing insights gained from the literature review and identifying open questions that this thesis aims to address. **Chapters 4 through 7** describe four experimental studies designed to examine the complex interrelationships between age, global cognitive impairment, specific cognitive functions, musical experience, and beat perception, and how these factors influence the ability to synchronize motor output with external rhythms. Finally, in **Chapter 8**, I integrate the results of the current studies with existing literature and discuss prospects for future research.

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Chapter 2

Sensorimotor synchronization in healthy aging and neurocognitive disorders

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Sensorimotor Synchronization in Healthy Aging and Neurocognitive Disorders

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Sensorimotor synchronization (SMS), the coordination of physical actions in time with a rhythmic sequence, is a skill that is necessary not only for keeping the beat when making music, but in a wide variety of interpersonal contexts. Being able to attend to temporal regularities in the environment is a prerequisite for event prediction, which lies at the heart of many cognitive and social operations. It is therefore of value to assess and potentially stimulate SMS abilities, particularly in aging and neurocognitive disorders (NCDs), to understand intra-individual communication in the later stages of life, and to devise effective music-based interventions. While a bulk of research exists about SMS and movement-based interventions in Parkinson's disease, a lot less is known about other types of neurodegenerative disorders, such as Alzheimer's disease, vascular dementia, or frontotemporal dementia. In this review, we outline the brain and cognitive mechanisms involved in SMS with auditory stimuli, and how they might be subject to change in healthy and pathological aging. Globally, SMS with isochronous sounds is a relatively well-preserved skill in old adulthood and in patients with NCDs. At the same time, natural tapping speed decreases with age. Furthermore, especially when synchronizing to sequences at slow tempi, regularity and precision might be lower in older adults, and even more so in people with NCDs, presumably due to the fact that this process relies on attention and working memory resources that depend on the prefrontal cortex and parietal areas. Finally, we point out that the effect of the severity and etiology of NCDs on sensorimotor abilities is still unclear: More research is needed with moderate and severe NCD, comparing different etiologies, and using complex auditory signals, such as music.

Keywords: aging, dementia, rhythm, finger tapping, timing, Alzheimer's disease, music, neurodegenerative diseases

INTRODUCTION

Sensorimotor synchronization (SMS) is defined as temporal coordination of a motor rhythm with an external rhythm. It is a form of adaptive interaction with the environment (Schwartze et al., 2011). Being able to synchronize to regularities in temporal structure and matching one's movements to those of others is of obvious importance in activities whose essence is based on creating a shared temporal structure, such as dance or joint music making (Sebanz et al., 2006). However, organizing one's own behavior according to the dynamic unfolding of events in the environment is crucial to many more situations than that. Interpersonal entrainment is a key rhythmic feature in human interactions, including non-musical interactions (Bispham, 2006). Many situations that do not require synchrony nonetheless cause people to synchronize their movements to each other, such as when people unintentionally synchronize their postural sway (Shockley et al., 2003) or lower limb movements while walking (van Ulzen et al., 2008; Nessler and Gilliland, 2010), or entrain the frequency of their movements to each other while clapping hands. While the use of a pulse in structuring one's behavior in time is self-evident in musical activities in which the goal is to maintain temporal stability, a pulse also appears in a more loose and subconscious way in interpersonal turn-taking interactions (Bispham, 2006). Spoken language contains remarkable temporal regularities in the signal envelope of the produced acoustic signal, as well as in vocal tract movements and syllable duration and rate (Poeppel and Assaneo, 2020). When comparing linguistic groups, correlations between aspects of temporal structuring in music emerge (Patel and Daniele, 2003) underscoring the universality of attending to regularities in auditory signals generally. Dynamic attending theory (Jones, 1976; Large and Jones, 1999) proposes that when presented with an auditory sequence, listeners' attention will oscillate periodically such that it is higher on the beat than off the beat, to allow for optimal processing and forming the basis for prediction. Although dynamic attending theory has mainly been used to explain phenomena of rhythmic perception in relation to sequences that are musical or isochronous (i.e., periodical with a constant interval between beats), it has also been proposed to explain interactional synchrony between people that happens in a less strictly rhythmic fashion (Cason et al., 2017). While language does not follow an isochronous rhythm, it is nonetheless based on temporal regularities, facilitating understanding by allowing the listener to predict incoming auditory input (Byrd and Saltzman, 2003; Port, 2003). In a domain-general fashion, entrainment to regular auditory input may thus enhance the representation of regularities in sound, guiding one's attention to point in time at which meaningful information is being delivered (Obleser and Kayser, 2019; Mathias et al., 2020). Accordingly, the perceptual system appears to be tuned to the natural rhythm of speech (frequencies between 2 and 8 Hz; Poeppel and Assaneo, 2020) Contrariwise, problems to perceive regularities in the environment and tune one's attention to them might hamper interpersonal communication. Indeed, it has been demonstrated that an inability to perceive a beat in music generalizes to a weakness in perceiving periodicities in speech (Lagrois et al., 2019). In other words, measuring a person's ability to perceive and synchronize with rhythms in the environment does not only reveal that person's sense of rhythm, but a more general propensity to predict events in the environment and relate to others.

It is therefore worthwhile to assess and study SMS abilities. However, the effect of age and neurocognitive disorders (NCDs) on sensorimotor abilities remains understudied. NCDs are a growing health concern to which an effective treatment remains elusive. Besides cognitive decline and degradation of memory performance, a common consequence of this condition is a decrease in the quality of social relationships. Decreased interactions with others and the environment is common to patients with dementia (Colling, 2000), a potential result of sensory decline common to old age (Gates and Mills, 2005; Correia et al., 2016) and to NCDs (Armstrong, 2009; Hardy et al., 2016; Brenowitz et al., 2019), or a consequence of living in isolation or in an inpatient context with insufficient social stimulation (Chung, 2004; Kolanowski et al., 2006). Nonetheless, this impairment in communication might also be understood as an impairment in the detection of regularities in the environment (Hoehl et al., 2021). Stimulating and training someone's sensorimotor abilities might inadvertently restore their capacity to predict events in the environment, and to relate successfully to others.

Music-based interventions, which are increasingly suggested in the treatment of NCDs [Guideline Adaptation Committee, 2016; National Institute for Health and Care Excellence (NICE), 2019], might reach their peak of effectiveness if they successfully stimulate SMS (Ghilain et al., 2019; Hobeika and Samson, 2020), particularly in those individuals whose motor abilities remain relatively unimpaired despite decline in other domains. Music-based interventions exist in many forms but those that encourage active participation appear to bring greater benefits on behavioral and psychological variables than those in which patients listen passively (Sakamoto et al., 2013; Särkämö et al., 2014), suggesting an important role of SMS in the effectiveness of these interventions. First, moving in time with others has been shown to promote feelings of social cohesion, prosocial attitudes, and cooperative behavior (Wiltermuth and Heath, 2009). Second, temporal expectations elicited by the perception of a musical beat may stimulate the reward network and induce pleasure (Salimpoor et al., 2011). Improving a person's temporal prediction abilities might help them synchronize and interact with others (Pecenka and Keller, 2011), and therefore improve communication and reduce isolation.

At present, motor abilities have been well examined in patients with Parkinson's disease (Grahn and Brett, 2009; Dalla Bella, 2018) but studies investigating SMS skills in other neurological diseases (notably NCDs) are scarce. Even in the case of healthy physiological aging, little consensus exists in the literature as to whether sensorimotor skills are preserved in old age. With this review, we aim to shed light on the question of how SMS abilities develop in the late decades of life and over the course of NCDs. Additionally, we touch upon the possibility of using SMS as a diagnostic tool. Since NCDs are afflictions of the aging brain, it is important to disentangle NCD-related changes in SMS from those related to healthy aging. Throughout this review, we will use the terms major and mild NCD. Major and mild NCD are the current terms used in the *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; DSM-5; American Psychiatric Association, 2013) for what is otherwise referred to as dementia and mild cognitive impairment (MCI). Although technically NCD is a somewhat broader term, for example including cognitive impairment in young people caused by traumatic brain injury or HIV infection, we will use the term NCD when discussing studies that themselves might have used the terms dementia or MCI in their nomenclature. In any case, all studies about NCDs reviewed here involved elderly subjects. Finally, Parkinson's disease is often discussed in the context of NCDs, and indeed "major/mild NCD [possibly] due to Parkinson's disease" exist as conditions in the DSM-5. However, Parkinson's disease is primarily a movement disorder, and as such, there already exists a bulk of literature regarding motor abilities in this population (Grahn and Brett, 2009; Grabli et al., 2012) as well as the use of rhythmic stimulation in rehabilitation (Dalla Bella et al., 2017a; Cochen De Cock et al., 2018; Dalla Bella, 2018), so we do not wish to add to this literature and restrict our review to the other, mostly cortical, etiologies of NCD, such as Alzheimer's disease (AD), vascular NCD, or NCD with multiple etiologies.

Our review is therefore organized as follows: First, after clarifying what is meant by SMS and how it is quantified and assessed, we present the cognitive and brain mechanisms that lie at the heart of SMS, in general terms and as a function of the more specific task requirements. Next, we give an overview of how the aging process influences cognitive performance and brain structure and function, followed by a section on how these processes are influenced by NCDs. In both cases, we offer some predictions with regard to SMS performance. We then review the available literature on SMS in healthy aging, followed by the literature on SMS in NCDs to evaluate the predictions we made. We conclude with some suggestions for future research.

Sensorimotor Synchronization: Common Paradigms and Ways of Assessing Performance

Synchronizing one's movement with an external rhythm can come in many forms including moving one's limbs with an auditory sequence, walking, or dancing (Repp and Su, 2013). However, the most commonly employed paradigm is that in which a participant is asked to produce regular, rhythmic taps with a finger. In the context of this review, we refer to two main types of tapping paradigms as unpaced tapping and paced tapping. Unpaced tapping corresponds to tasks in which participants produce movements at a self-generated rate, very often to identify someone's spontaneous motor tempo (SMT) but also to assess how fast or slow one can maintain a regular rate. Paced tapping, on the other hand, consists of synchronizing one's tapping to an auditory pacer. This pacer can be a simple isochronous (metronomic) sequence, with the goal to match each tap to the onset of each beat, but it can also be a more complex stimulus (such as music) where the beat must be inferred. Very often, the participant continues to do this until the signal fades, a case to which we refer as *synchronization without continuation*, to distinguish it from *synchronization–continuation*, that is, tasks in which participants first synchronize their tapping with an auditory pacer, but then continue tapping at the same speed for some time after the stimulus has faded.

Sensorimotor synchronization performance measured by these tasks is described in terms of variability and accuracy. When the participant synchronizes to an external metronome or rhythmic stimulus, accuracy or beat alignment refers to the extent to which taps occur before (negative asynchrony) or after (positive asynchrony) the beat (event onset in the external rhythm) and is thus expressed as a difference in ms. Variability or precision refers to the standard deviation of the asynchronies. On the other hand, during continuation tapping, the main observable is the inter-tap interval (ITI), and its average and standard deviation are reported. Mean ITI reflects whether the subject drifts away from the original tempo, while ITI variability, or precision, refers to how consistently an individual's taps are distributed around a period and is given by the standard deviation (SD) of the ITIs within a trial, or the coefficient of variation (CV; SD divided by mean ITI). Sometimes, variability is expressed as its inverse, consistency. Finally, mean ITI (reflecting average speed) and ITI variability are also used as outcomes in self-paced tapping, in the absence of an external stimulus.

BRAIN AND COGNITIVE MECHANISMS INVOLVED IN SENSORIMOTOR SYNCHRONIZATION

Which brain networks are involved in SMS tapping depends on the exact nature and instructions of the task, but very generally, areas involved in tapping tasks are primary sensory and motor cortices, supplementary motor area (SMA), anterior cerebellum, dorsolateral prefrontal cortex, premotor cortex, parietal areas, and the basal ganglia (Larsson et al., 1996; Rao, 1997; Penhune and Doyon, 2005; Molinari et al., 2007; Chen et al., 2008; Witt et al., 2008; Kung et al., 2013; Repp and Su, 2013). Another general observation that can be made across a variety of timing tasks is that there seem to be two somewhat disparate networks for processing intervals depending on the length of the inter-onset interval (IOI; Repp and Su, 2013). The automatic timing network is involved in the processing of sub-second intervals and includes the primary motor cortex, the SMA, the premotor cortex, and the cerebellum (Lewis and Miall, 2003). The cognitively controlled timing network is involved in the processing of intervals longer than 1 s. It comprises areas of the parietal cortex, prefrontal cortex, and the basal ganglia (Lewis and Miall, 2003; Buhusi and Meck, 2005; Koch et al., 2009; Coull et al., 2011, 2013; **Figure 1**).[1] The basal ganglia, universally involved in beat processing (Grahn, 2009), are also considered part of the automatic timing network by some (Lewis and Miall, 2003; Koch et al., 2009), but not all authors (Buhusi and Meck, 2005), although, as Coull et al. (2011) point out, it may well be that different nuclei within the basal ganglia are responsible for timing in the sub- and supra-second range, respectively. Contrary to the

[1]https://www.nitrc.org/projects/mricrogl/

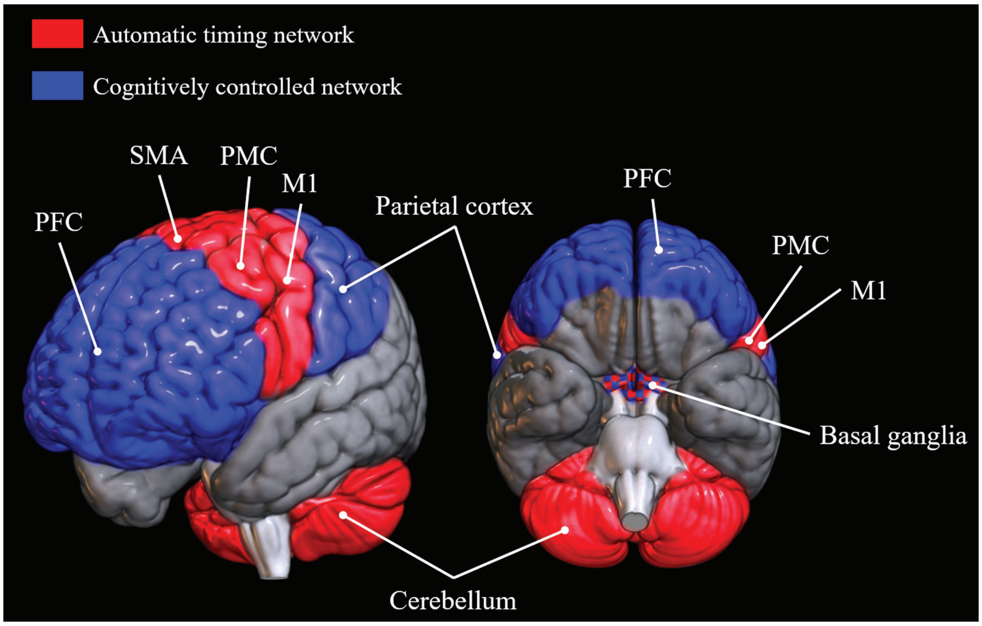

FIGURE 1 | Brain areas reported to be active in tasks requiring automatic timing and cognitively controlled timing, respectively (Lewis and Miall, 2003; Buhusi and Meck, 2005; Koch et al., 2009; Coull et al., 2011, 2013; Repp and Su, 2013). Brain networks were plotted onto a standard MNI152 template rendered with the open-source software MRIcroGL (McCausland Center for Brain Imaging, University of South Carolina). PFC, prefrontal cortex; SMA, supplementary motor area; PMC, premotor cortex; M1, primary motor cortex.

automatic timing network, the cognitively controlled timing network is based on brain areas involved in high-level cognitive functions. Indeed, Coull et al. (2011, 2013) suggest that explicit estimation of current stimulus duration is a conscious cognitive operation necessary to perceive periodicity in a slow stimulus with an interval length of above around 1 s. In a related manner, for the successful perception of and synchronization to a slow beat, people might employ tactics, such as explicit counting (Grondin et al., 1999) and/or subdivision of the given interval (Repp, 2003; Repp and Doggett, 2007), strategies that arguably rely more on attentional and memory processes and corresponding brain networks and less on pure more mechanisms and structures. According to Koch et al. (2009), the dorsolateral prefrontal cortex's role in the timing of long intervals might be related to WM. A study by Henley et al. (2014) supports this idea, as they observed correlations between the ability to maintain a slow beat and their WM capacity, measured with the digit span backwards test (Wechsler, 1981).

Unpaced Tapping

As mentioned in the previous section, unpaced tapping tasks are frequently in such a manner that one's natural, SMT is measured. SMT tends to be consistent across repeated measures within the same participant and is seen as a reliable metric of internal tempo or clock (Denner et al., 1964). In addition, one might look at preferred perceptual tempo, which is a perceptual analogue to SMT.

In cognitive terms, results of spontaneous tapping studies have been explained in terms of an internal clock mechanism. Many authors have argued that people possess an internal clock which determines not only at which tempo they comfortably synchronize their movements, but also their ability to predict how events in the environment unfold over time (McAuley et al., 2006; Turgeon and Wing, 2012). Such an internal clock is often conceptualized as a pacemaker emitting pulses and a reference memory evaluating time by counting the number of pulses emitted (Church, 1984).

Some evidence suggests that tapping at a self-determined speed, as opposed to synchronizing one's movement with an external pacer, engages particularly the primary motor cortex, premotor cortex, SMA, dorsolateral prefrontal cortex, as well as areas of the parietal lobe and cerebellum (Larsson et al., 1996; Witt et al., 2008). Furthermore, a lesion study involving patients with basal ganglia pathology also demonstrated that self-paced tapping may depend on basal ganglia integrity, as patients tapped at more heterogeneous rates and with increased variability compared to healthy controls (Schwartze et al., 2011). The authors posit that self-paced tapping might specifically depend on the integrity of connections between pre-SMA and striatum.

Besides paradigms to identify a person's SMT, unpaced tapping can also take the form of tasks in which participants tap as fast or as slow as possible while maintaining a continuous regular rhythm. Tapping at a fast rate might engage the same automatic timing network, but might additionally depend on factors like the time required for muscle contractions and muscular and joint flexibility (Daley and Spinks, 2000; Carmeli et al., 2003). However, synchronization precision at a very fast tempo might additionally require attentional resources, as suggested by a study that found a correlation (Colella et al., 2021) between variability of tapping and score on the Frontal Assessment Battery, a test of frontal lobe integrity said to reflect attention (Dubois et al., 2000). Tapping at a very slow rate, on the other hand, might involve a conscious representation of the current interval and a memory aspect, likely implicating structures from the cognitively controlled network (**Figure 1**).

Paced Tapping

As mentioned above, we distinguish between simple synchronization tasks without continuation and synchronization–continuation paradigms. The former type of task is expected to engage the motor circuitry associated with timing tasks, such as motor cortical areas, cerebellum, and basal ganglia, with some studies suggesting even stronger involvement of the premotor cortex and cerebellum with such externally paced movement than when a tempo is internally maintained (Del Olmo et al., 2007; Kornysheva and Schubotz, 2011), like in the continuation phase of synchronization–continuation tasks. While a few studies suggest the same areas to be involved in continuation as in synchronization (Jäncke et al., 2000; Jantzen et al., 2004), continuation tapping after an external stimulus has faded might elicit additional activation in primary sensory and motor cortices (Gerloff et al., 1998), premotor cortex, SMA (Serrien, 2008), thalamus, and basal ganglia (specifically, putamen; Lewis et al., 2004). One study also demonstrated that a prefrontal–parietal–temporal network, containing the dorsal and ventral prefrontal cortex, middle temporal gyrus, and parietal lobes, may be especially activated during continuation tapping (Jantzen et al., 2007). The authors suggest that the involvement of the prefrontal cortex reflects the task's requirement to form an internal representation of the sequence tempo and to recruit attentive processes. This is supported by a study finding prefrontal white matter integrity to be related to variability of tapping in the continuation phase of a synchronization–continuation task (Ullén et al., 2008).

Just like for unpaced tapping, the exact involvement of brain networks and cognitive mechanisms may vary depending on sequence tempo in tasks involving synchronization with and without continuation alike. Accordingly, we can expect particular recruitment of structures like the prefrontal cortex and the parietal lobes (the cognitively controlled timing network) in paced tapping at speeds beyond 1 s (Koch et al., 2009).

BRAIN AND COGNITIVE CORRELATES OF HEALTHY AGING AND NEUROCOGNITIVE DISORDERS

Healthy Aging

Even in the absence of neurodegenerative disease, the aging brain is subjected to global cortical atrophy and loss of functional integrity. Particularly affected structures are the frontal lobes (Kaup et al., 2011) and the hippocampus (Persson et al., 2006). Reduced cortical volume has also been demonstrated in the parietal cortex (Kalpouzos et al., 2012), and functional connectivity between parietal regions and prefrontal cortex has been shown to be reduced in aging (Madden et al., 2010). With these structures impacted in old age, it is not surprising that aging is associated with deficits in WM and attention in particular (Grady, 2012; Harada et al., 2013). Conversely, genetic markers of aging have been shown to accumulate more slowly in the cerebellum than in other parts of the brain (Liang and Carlson, 2020). Given the cerebellum's role in precise motor timing (Bastian, 2006; Bares et al., 2007), this points to a possible preservation of timing abilities in old age. Additionally, the motor cortex does not belong to the heavily impacted structures in normal aging, but some atrophy in motor cortical regions has been observed, together with atrophy in the corpus callosum (Seidler et al., 2010). Functional neuroimaging has found different patterns of brain activation in motor tasks between older and younger people. More specifically, some motor tasks (especially fine motor control) engage motor regions in everyone, but additionally engage prefrontal and sensorimotor networks in aged people (Heuninckx et al., 2005, 2008; Seidler et al., 2010), even in cases where there are no age-related differences in performance. This might reflect a shift from more automatic to more controlled processing with age, in spite of the same task instructions and the same outcome (Heuninckx et al., 2005). In line with those results. a resting-state functional connectivity study also found a pattern of heightened connectivity in some motor networks (motor cortex and cerebellar lobule VIII with putamen) and decreased connectivity in others (cerebellar lobule V and VIII with sensorimotor portion of insular cortex; Seidler et al., 2015). All these results might point to a mechanism of compensation, in which motor cortex pathology in old age is offset by an additional use of other domain-general neural resources, among others in the prefrontal cortex. This might also explain relations between sensorimotor function and cognitive functions in age (Li and Lindenberger, 2002). If motor tasks rely more on prefrontal cortex and other networks in old age, we would assume a covariation of motor performance and cognitive functions, and competition of resources if a task involves both motor and cognitive requirements. Alternatively, the additional involvement of non-motor regions in older people might also reflect a less efficient use of neural resources in older people (Stevens et al., 2008; Grady, 2012).

This picture of age-related changes in cognitive functions and neural mechanisms generates some predictions. If we imagine internal clock in terms of a pacemaker emitting regular pulses and a person's SMT as "one tap every n pulses," and if we suppose that internal clock slows with age, as has often been suggested (Vanneste et al., 2001; Turgeon and Wing, 2012), this means that the rate of regularly emitted pulses is lower with age. Consequently, SMT and preferred perceptual tempo should be lower with age, but we do not have a reason to believe that people would tap spontaneously with a higher variability. If one chooses their own tempo and provides one tap every n pulses, even if these pulses occur less frequently, variability is not expected to be affected. On a cerebral level, the relative preservation of cerebellar integrity (Liang and Carlson, 2020) also suggests preserved variability in spontaneous tapping, given the cerebellum's role in predictive movement control (Bastian, 2006). However, on fast unpaced tapping tasks, we expect a slower speed as well as reduced consistency. As mentioned above, CV when tapping as fast as possible has been linked to attention (Colella et al., 2021), and we expect lower available attentional resources in aging to be reflected in lower consistency.

Regarding paced tapping, due to the relative preservation of cerebellum and motor cortical structures in aging, we do not expect a great decline in performance in elderly people, at least at intervals that are neither very fast nor very slow, except perhaps for very old people. With regard to synchronization to very fast stimuli, we might imagine lower consistency. If an internal pacemaker emits fewer pulses with age, this should lead to a reduced temporal resolution of perceived stimuli and therefore increasing difficulty to synchronize to them as interval length decreases. Conversely, due to the asserted use of the cognitively controlled timing system with very slow intervals (above 1 s), we would expect differences in brain activation with aging. As the memory and attentional resources might already be used for fundamental motor synchronization due to compensatory rewiring, we hypothesize a larger involvement of parietal areas and prefrontal cortex to fulfill those requirements, and/or a decrease in performance.

Neurocognitive Disorders

In order to describe the neuropathology of NCDs and make predictions regarding SMS in cognitively impaired people accordingly, it is important to acknowledge that NCD is a complex clinical picture that can have several different etiologies, including AD, vascular NCD, frontotemporal NCD, NCD with Lewy bodies, and others.

Most of the brain structural damage in NCDs, especially in AD, occurs in the hippocampus and surrounding parietal–temporal areas, even in early stages of the disease (Braak and Braak, 1991; Scheff et al., 2006; Jacobsen et al., 2015; Rémy et al., 2015). Besides the hippocampus, there is reduced structural and functional integrity in the prefrontal cortex (Braak and Braak, 1991; Rémy et al., 2015). WM and attention capacity are reduced, beyond what is usual with healthy aging. Conversely, primary sensory, motor, visual and anterior cingulate cortices are relatively well preserved (Jacobsen et al., 2015). However, despite cortical atrophy affecting some structures more than others, the entire cortex is affected and particularly in late stages of the disease, motor areas show the same neurofibrillary tangles and neurotic plaques as other areas, as some autopsy studies reveal (Golaz et al., 1992; Suva et al., 1999). Some research even suggests that motor cortex atrophy occurs in early stage NCD, although motor symptoms are visible only in later stages of the disease. Similarly to healthy aging, there is some evidence for compensatory processes: One study reported hyperexcitability of the sensorimotor cortex in AD patients compared to age-matched controls, even in the absence of motor symptoms (Ferreri et al., 2016). A diffusion tensor imaging study demonstrated some rewiring with alternative connectivity between motor cortex and other cortical and subcortical areas in AD and MCI (Agosta et al., 2010). Additionally, this level of rewiring was correlated with hippocampal atrophy and AD-related changes in grey matter volume. It is conceivable that these NCD-related changes reflect an attempt to compensate for degeneration of motor structures by employing additional brain networks to perform motor tasks.

Even AD can be considered a somewhat heterogeneous disease that could possibly be further divided into subtypes (Lam et al., 2013). In vascular NCD, the second most common type, the brain damage depends on the location of the vascular accident. It can be primarily cortical, primarily subcortical, or a combination, and the neuropsychological profile is accordingly variable (Braaten et al., 2006; O'Brien and Thomas, 2015). In short, NCD is a diverse clinical picture, and even its subtypes can further be divided into subcategories, so it is difficult to make predictions with regard to SMS performance. The following predictions, as well as the results discussed later, might to some extent be generalizable, but apply to AD patients more than to people with other NCDs.

Generally, there is not too much evidence to suggest that people with NCDs would perform worse on unpaced tapping tasks. However, given that self-paced tapping has been shown to depend more on dorsolateral prefrontal cortex and parietal lobe integrity (Witt et al., 2008), it could be that accuracy and consistency might be lower in people with NCDs. Additionally, it must be mentioned that unpaced tapping might be differently affected by different patterns of neural degeneration. For example, basal ganglia pathology is particularly associated with vascular NCD (Hansen et al., 2015; Banerjee et al., 2017), so maybe people with vascular NCDs, and particularly those with damage to the basal ganglia, might be more impacted in unpaced tapping tasks, which may rely more heavily on basal ganglia (Schwartze et al., 2011), as discussed above.

Regarding paced tapping tasks, as with healthy aging, the degree to which people with NCDs might be impaired might especially depend on interval length. Since motor structures, including the cerebellum, are relatively well preserved in people with NCDs, we expect relatively good performance when using the automatic timing network, that is, at fast and comfortable intervals, and especially at tasks using synchronization without continuation, that is, without a requirement to create a mental representation of a given interval. We might expect some difficulty, reflected in higher variability in people with NCDs compared to healthy participants on synchronization–continuation tasks, since continuation tapping involves WM and structures like the prefrontal cortex, parietal and temporal lobes are implicated, all of which are more impacted in NCDs than in healthy aging. Besides higher variability, we hypothesize people with NCDs to speed up on continuation tapping at slow tempi, given that speeding up on such tasks has previously been related to performance on WM tasks (Henley et al., 2014). We could conjecture that tapping at slow tempi would be even more impaired in people with frontotemporal NCD, since here the prefrontal cortex is especially impaired. Perhaps strategies like explicit counting and subdivision that can help people to synchronize with slow sequences are also less utilized by people with NCDs than by their healthy counterparts.

TABLE 1 | Studies investigating spontaneous motor tempo in different age groups.

Study		Young	Middle-aged	Old	Very old
Baudouin et al. (2004)	*n*	20	–	21	21
	M_{Age} (SD)	25.05 (3.71)		73.19 (4.54)	85.90 (3.32)
	SMT in ms (SD)	654^{***a} (186)		$1,072^{***a}$ (318)	$1,125^{***a}$ (426)
McAuley et al. (2006)	*n*	119	52	25	21
	Age range	18–38	39–59	60–74	75–95
	SMT in ms (SD)	630^{**b} (22)	522^{**b} (34)	632^{**b} (59)	648^{**b} (43)
Age significantly predicted SMT**					
Turgeon and Wing (2012)	*n*		60		
	M_{Age} (SD_{Age})		54.35 (25.18)		
	SMT				
Age significantly predicted SMT***					
Vanneste et al. (2001)	*n*	8	–	11	–
	M_{Age} (SD)	26.25 (1.83)		69 (4.52)	
	SMT in ms (Range)	536** (283–727)		747** (625–1,035)	

M, mean; SD, standard deviation; SMT, spontaneous motor tempo. [a]*Old and very old groups significantly different than young group; no difference between old and very old.* [b]*No statistical test for between-group differences was performed, but a regression analysis found age to significantly predict SMT.* $^{**}p<0.01$; $^{***}p<0.001$.

SENSORIMOTOR SYNCHRONIZATION IN HEALTHY AGING

In the following, we discuss and synthesize some of the relevant research that features tasks that make people of different ages tap in a rhythmic fashion, to test the predictions we made. We report separately on unpaced and paced tapping tasks, which both contribute complementary information about how temporal mechanisms change with age. Previous research has demonstrated that people (regardless of age or cognitive impairment) spontaneously produce intervals of around 600 ms (Dalla Bella et al., 2017b) and that synchronization to external rhythms is best between 400 and 800 ms (McAuley, 2010), thus suggesting a relationship between these two measures in the sense that synchronization consistency and accuracy may become smaller as the difference between target tempo and internal tempo becomes greater.

Unpaced Tapping

Spontaneous Motor Tempo

Studies that have compared SMT across age groups generally agree with each other in that they find a significantly slower tempo in older compared to younger people (Vanneste et al., 2001; Baudouin et al., 2004; McAuley et al., 2006; Turgeon and Wing, 2012; see **Table 1**). It is merely the magnitude of slowing with age, as well as the exact developmental course, that were somewhat different across studies. For example, while some studies found quite substantial differences in the ITIs of participants of different ages (1,072 ms for old participants; 654 ms for young participants; Baudouin et al., 2004), this difference is smaller in other studies (747 ms in old participants; 536 ms in young participants; Vanneste et al., 2001) and even subtler in others (McAuley et al., 2006, found the SMT of people aged 75+ to be 648 ms, 632 ms for participants between 60 and 74, and 522 ms for people aged 39–59).

Regarding the developmental course, some authors demonstrated that it is especially in very old age that a slowing of SMT is visible. McAuley et al. (2006) found a cubic relationship between age and SMT, suggesting that this variable slows particularly late in life (i.e., after the age of 75). Similarly, in study of Turgeon and Wing (2012), a slowing of spontaneous motor rate was visible particularly in participants aged 75 and above.

Consistency of spontaneous tapping, which is usually expressed in terms of CV, does not appear to be as affected by age, as we predicted. McAuley et al. (2006) and Vanneste et al. (2001) found that old and very old people at their preferred tempo tapped as consistently as young ones. Along similar lines, using linear regression, Turgeon and Wing (2012) did not find age to predict a significant proportion of variance of CV. Thus, at a tempo that participants choose themselves, differences in terms of consistency have not been observed between young and old people.

As SMT reflects one's natural rate of rhythmic motor activity, it is often thought of as being related to preferred perceptual tempo. McAuley et al. (2006) investigated the relationship between SMT and preferred perceptual tempo, in a study in which they presented rhythmic sequences of different speeds to their participants and asked them to judge whether each sequence was too fast, too slow, just right (relative to their favorite speed), or anything in between. They found that preferred perceptual tempo slowed with age along with SMT and that these two variables were highly correlated. One may then conclude that SMT, which appears to significantly slow down with age, might reflect the slowing of one's internal clock in old age.

Fastest and Slowest Unpaced Tapping

Other types of unpaced tapping are those that require participants to tap in a repeating, continuous fashion as fast or as slow as possible, to see at which upper and lower limit participants are able to maintain a regular tap. As demonstrated by a large number of studies, when given the instruction to tap regularly

TABLE 2 | Studies investigating paced tapping in different age groups.

Study		Fast tempo (<350 ms)		Comfortable tempo		Slow tempo (>1,000 ms)	
		IOI	Age effect	IOI	Age effect	IOI	Age effect
Bangert and Balota (2012)	Consistency	–		500 ms/1,000 ms	No diff.	1,500 ms	O<Y***
	Accuracy				No diff.		O<Y*
Carment et al. (2018)	Consistency	333 ms	No diff.	500 ms/1,000 ms	No diff	–	
	Accuracy		O<Y***		No diff.		
Drewing et al. (2006)	Consistency	333 ms	No diff.	999 ms	No diff.	–	
	Accuracy		No diff.		No diff.		
Duchek et al. (1994)	Consistency	–		550 ms	No dif.	–	
	Accuracy			550 ms	No diff.		
Krampe et al. (2005)	Consistency	300 ms	No diff.	400 ms/600 ms/800 ms/1,000 ms	No diff.	1,200 ms/1,600 ms/2,000 ms	No diff.
	Accuracy		No diff.		No diff.		No diff.
Krampe et al. (2010):	Consistency	–		550 ms	No diff.	2,100 ms	No diff.
Single-task condition	Accuracy				No diff.		No diff.
Dual-task condition	Consistency				O<Y***		O<Y*
	Accuracy				O<Y*		O<Y**
McAuley et al. (2006)	Consistency	150 ms/225 ms/337 ms	No diff.	506 ms/759 ms	No diff.	1,139 ms/1,709 ms	No diff.
	Accuracy		No diff.		No diff.		O>Y
Nagasaki et al. (1988)	Consistency	200 ms/250 ms/333 ms	O<Y*	500 ms/1,000 ms	O<Y*	–	
	Accuracy		No diff.		No diff.		
Thompson et al. (2015)	Consistency	–		500 ms/667 ms	O<Y***	–	
	Accuracy				O<Y*		
Turgeon et al. (2011)	Consistency	–		600 ms/900 ms	No diff.	–	
	Accuracy				No diff.		
Vanneste et al. (2001)	Consistency	300 ms	No diff.	400 ms/500 ms/600 ms/700 ms	No diff.	–	
	Accuracy		No diff.		No diff.		

*For simplification, paradigms using synchronization with continuation and synchronization–continuation are reported together here. O, old participants; Y, young participants; IOI, inter-onset interval. *p<0.05; **p<0.01; ***p<0.001.*

as fast as possible, older people tapped at a slower rate than younger people (Nagasaki et al., 1988; Cousins et al., 1998; McAuley et al., 2006; Turgeon et al., 2011). This fastest tempo may slow down most evidently from the age of about 70 years onwards (McAuley et al., 2006). Conversely, McAuley et al. (2006) also made their participants tap as slowly as possible at a constant rate, in which case older people sped up more than younger people. It appears, then, that aged people have a narrower range of tempi at which they can consistently produce taps than young people.

The variability of taps at a fastest regular speed has not always been investigated. Where it has, CV was shown to be affected by aging, although this effect was weaker than the effect of aging on interval size. More specifically, Turgeon et al. (2011) found age to account for 7% of the variance in CV scores and for 32% of the variance in ITI, which might reflect decreased attention in old age.

Paced Tapping

Synchronization Without Continuation

In tasks requiring participants to synchronize their tapping with an external regular signal, differences between young and old have been less clear than in the unpaced tapping tasks described above (see **Table 2**). First of all, several studies did not find differences between these two groups in terms of variabilities or accuracies (Krampe et al., 2005; Drewing et al., 2006; Turgeon et al., 2011). Contrary to that, Nagasaki et al. (1988) did find CV to correlate with age at all the intervals examined (between 200 and 1,000 ms), but did not find a significant effect of age on asynchronies.

One study (Thompson et al., 2015) did report differences between old and young participants in both variabilities and accuracies. In this study, older adults (age range 51–80) tapped to a regular beat with a higher variability and with a larger asynchrony than younger and middle-aged adults (age range 18–43). These results may seem surprising, especially in light of the relatively young age of their old adults group ($M_{Age} = 63.67$; for comparison, Drewing et al., 2006 did not find such age-related effects in the group of people aged 78–88). However, the difference found by Thompson et al. (2015) may, at least in part, be explained by musical experience. Since the authors were interested in how musical experience influenced beat synchronization, they recruited many musically experienced participants (in the young and middle-aged adult groups, there were 32 people with and 11 people without musical background). However, musical background was not assessed in the group of older adults, and therefore old and young adults may have not been matched on this variable. In fact, the respective asynchronies found in this study (around 40 ms before the beat for the older group and around 15 ms before the beat for the younger groups) are remarkably close to values that have previously been found in research comparing musicians and non-musicians (Aschersleben, 2002). Assessing musical training in all groups, including older adults, would have made it possible to verify whether young and middle-aged adults' superior performance was due to musical experience rather than age, and also to investigate whether musical training could be a neuroprotective factor in aged people.

Up until now, all studies we discussed here described paradigms in which people synchronized their movements to an isochronous sequence of repeating single beats. And in fact, while a large part of those studies discussed their results in terms of their relevance for music perception and cognition, one could argue that their stimuli were not strictly musical. People move spontaneously to a musical beat (Leman et al., 2017), even though this beat is a perceptual construct that does not have a clear physical correlate. Beats sometimes co-occur with musical notes, but not necessarily: A beat can occur on a silent event (McAuley, 2010). Extracting a beat from a complex auditory signal, such as music, while automatic, might be a quite different process than merely synchronizing to an explicit beat. And therefore, this process might be differently affected by aging and NCDs. Indeed, rhythm difficulties might be more easily identified with music than with simple, repeating tones (Sowiński and Dalla Bella, 2013; Falk et al., 2015). Another reason to look at music in addition to metronomic sequences is that generally, people tend to tap with a higher asynchrony (that is, their taps precede the corresponding stimulus onset) when synchronizing with a metronome compared to music (Thaut et al., 1997; Aschersleben, 2002), a result that has recently been confirmed in elderly people (Ghilain et al., 2020a,b), but still lacks a definitive explanation. It has been suggested that subdivision of intervals between beats leads to a reduction of negative asynchronies and their variability, and that synchronization may be facilitated by the recurrence of different pitches, event duration, or intensities (Repp, 2003). In this way, music could be seen as an extreme case of subdivision, and the observed pattern of reduced asynchronies in tapping to music might be no different from what has been observed in tapping to a subdivided metronomic sequence. In either case, however, no studies exist to the best of our knowledge that compare old and young participants on an SMS task requiring participants to tap along with an auditory complex, that is, musical, stimulus.

Synchronization–Continuation

In synchronization–continuation tasks, participants first synchronize with a metronome and then continue tapping at the same rate when the sound has stopped. Generally, only the performance in the continuation phase is analyzed (Wing and Kristofferson, 1973). Regarding the question of how older adults perform in this paradigm, the results are somewhat mixed (see **Table 2**). Turgeon et al. (2011) used a synchronization–continuation paradigm in which the target tempi per individual were determined based on one's SMT in the preceding spontaneous tapping task (see Section "Spontaneous Motor Tempo"). At the intervals IOI = 600 ms and IOI = 900 ms, age did not significantly predict variability or accuracy.

Other studies also did not find any differences in ITI or variability on synchronization–continuation tasks using tempi between 300 and 700 ms (Duchek et al., 1994; Vanneste et al., 2001). One study found intact performance in old subjects even at intervals as short as 150 and 225 ms (McAuley et al., 2006), but a higher asynchrony (speeding up) at the slowest target interval (1,709 ms) in their oldest group (75 years and above), but not in the group of 60–74-year-olds. Conversely, Carment et al. (2018) reported an increase in variability among older subjects at the IOI of 333 ms, but not at 500 and 1,000 ms. Another study found differences in both variability and accuracy among older participants at a target interval of 1,500 ms, but not at 500 ms or 1,000 ms (Bangert and Balota, 2012). These results lend support to the purported existence of two systems involved in temporal perception, an automatic and a cognitively controlled one, the latter of which is particularly implicated in the processing of slow intervals and presumably used less efficiently by older people.

Krampe et al. (2010) conducted a study with a dual-task design in which participants were required to tap to a faster (IOI = 550 ms) or slower (IOI = 2,100) tempo, while performing variants of the NBack WM task (Dobbs and Rule, 1989). In this task, participants were exposed to a sequence of visual stimuli and were asked to indicate when the current stimulus matched the one presented two steps earlier in the sequence. While this paradigm falls a bit outside the order of simple synchronization–continuation paradigms presented here, it is relevant for two reasons. First, the authors also report performance under single-task conditions, that is, while performing synchronization–continuation without a concurrent second task. In this case, there was no difference in variability or accuracy among age groups, even at the slow tempo of IOI = 2,100 ms, which is in contrast to the speeding up among oldest subjects in study of McAuley et al. (2006) study and the lower consistency and accuracy observed in oldest participants of Bangert and Balota (2012). This discrepancy might in part be explained by age differences: While older participants of Krampe et al. (2010) had a M_{Age} of 67, healthy old participants of Bangert and Balota (2012) were on average 75 years old and McAuley et al. (2006) included only people aged 75 or older in their oldest group. Therefore, it indeed appears to be difficult at least for very old people to synchronize successfully with a fading stimulus presented at a slow tempo (of at least an IOI = 1,200 or more).

The second reason for which study of Krampe et al. (2010) study is relevant to this review is that the dual-task nature of the paradigm might provide relevant information regarding the cognitive mechanisms involved in tapping at slow frequencies. Dual-tasking caused people regardless of age to speed up at the slow tempo, but additionally caused old participants to speed up at the fast tempo. Similarly, variability was significantly higher in older adults (at fast and slow tempi), but only in the dual-task condition. The authors' interpretation is that maintaining temporal precision and stability, even at a tempo of IOI = 550 ms, might be a quite automatic process in younger people, but might cost older people more attention and WM resources, in line with the compensation hypotheses mentioned above. Without any cognitive load, they can deploy that attention and WM resources to perform the task as well as their young counterparts. However, with fewer of these resources available,

TABLE 3 | Studies investigating spontaneous motor tempo and spontaneous tapping in people with and without neurocognitive disorders.

Study		Healthy	Mild NCD	Major NCD
Ghilain et al. (2020a)	SMT in ms (SD)		Between-group difference in SMT: n.s.	
	Consistency		Between-group difference in CV: n.s.	
Martin et al. (2017)	SMT in ms (SD)	820.33 (237.68)	–	935.88 (381.72)
	Consistency		*Not computed*	
Rabinowitz and Lavner (2014)	SMT in ms (SD)	581***	747***	
	Consistency		*Not computed*	
Roalf et al. (2018)	*n*	131	46	62
	SMT in ms (SD)	438*[a] (67)	468*[a] (102)	468*[a] (91)
	Consistency (IIV)	0.72*[a]	0.83*[a]	0.82*[a]

NCD, neurocognitive disorder; SMT, spontaneous motor tempo; SD, standard deviation; IIV, intra-individual variability; CV, coefficient of variation; n.s., not significant. [a]Major and mild NCD groups significantly different than healthy group; no difference between major and mild NCD.
**$p<0.05$; ***$p<0.001$.*

their performance will drop. Indeed, as we discussed in Section "Brain and Cognitive Correlates of Healthy Aging and Neurocognitive Disorders," it may be the cumulative effect of slow tempo, cognitive load, and age-related competition for prefrontal resources due to compensatory rewiring of the motor system that is expressed in the lower performance of older people.

Conclusion: Sensorimotor Synchronization in Healthy Aging

Perhaps the clearest finding regarding aging and SMS is a lower SMT in older people, which has been demonstrated in people in their 60s and above but may be most apparent from the age of around 75 years onward. Similarly, preferred perceptual tempo appears to slow with age and to correlate with SMT. In contrast, variability appears to be intact in old participants tapping at a self-chosen speed. Moreover, the range of rates at which aged participants can tap regularly is narrower than for young participants, with a slower fastest tempo and a faster slowest tempo.

Paced tapping tasks have not tended to reveal differences in variability or accuracy between old and young subjects. Exceptions are synchronization–continuation tasks where participants had to maintain a relatively slow rate beyond 1 s, in which older people tended to speed up and tap less consistently, especially very old people from around 75 years old. Higher variability has also been reported at fast intervals of 333 ms and below and some research points to an interaction between age and cognitive load even at intervals that are close to people's natural pace.

SENSORIMOTOR SYNCHRONIZATION IN NEUROCOGNITIVE DISORDERS

Unpaced Tapping

Spontaneous Motor Tempo

Having discussed the relative slowing of SMT with age, we now discuss how this variable is affected by NCD. A few sources have suggested that unpaced tapping may become more variable and SMT may slow in NCDs, especially in advanced stages (see **Table 3**). Roalf et al. (2018) found people with AD and MCI to tap with a higher variability compared to age-matched healthy controls, and variability was negatively associated with their score on the Mini-Mental State Examination (MMSE; Folstein et al., 1983), a widely used test for screening cognitive function among the elderly. People with AD produced significantly fewer taps during 1 min of tapping at a comfortable rate compared to healthy participants, whereas the speed of participants with MCI did not significantly differ from either of the other groups. The difference in produced ITI between the AD group and healthy older adults was significant, albeit not very large (469 and 441 ms, respectively). Similarly, Rabinowitz and Lavner (2014) found that in a group composed of patients with MCI and patients with a diagnosis of dementia, variability was higher in that group than in healthy controls. Moreover, patients tapped at a slower speed (747 ms) than their healthy counterparts (581 ms). Additionally, MMSE score was found to be correlated with mean ITI, suggesting a slowing of SMT with disease progression. In contrast, some other studies compared people with and without NCD on a spontaneous motor tapping task and did not find any differences in ITI or variability (Martin et al., 2017; Ghilain et al., 2020a). In these studies, subjects tapped at a comfortable speed for 30 s or for 30 ITIs, respectively. The apparent disagreement in the literature may be explained by different instructions that were given. The durations in which people performed the SMT task were shorter in Roalf et al. (2018; six blocks of 10 s) and Rabinowitz and Lavner (2014; one block of 15 s). In just 10 or 15 s, even when told to tap at a comfortable speed, people might feel pressure to produce as many taps as possible. Indeed, the produced ITIs were relatively low, even compared to the ITIs found in the studies on SMT in healthy aging (see **Table 1**). Although speculative, it may be that people with NCD react to this pressure differently than healthy older adults. Additionally, cognitively impaired people might potentially have had more problems understanding the task instructions. If, due to lack of clarity of the task requirements, people with NCD tapped more hesitantly (slower and more variably) in the beginning of a task, this would be reflected in their overall scores more heavily if the whole trial was just 10 or 15 s long.

Therefore, the SMT tasks used in Ghilain et al. (2020a) and Martin et al. (2017), affording their participants more time to establish a regular tapping pattern reflective of their internal speed, might be a better representation of their real SMT. Indeed, the rates observed in their studies, which lay roughly between 700 and 950 ms, are close to SMT values that have been observed in physiological aging (see **Table 1**). It therefore does not appear that during spontaneous tapping, ITI and consistency deteriorate in NCD, at least not in the mild to moderate stages of NCD that participants in all the studies quoted above tended to be in. More research, particularly including people with more severe NCD, is needed to establish an effect or absence of effect of NCD on SMT.

Fastest Unpaced Tapping

As with healthy aging, some studies have looked into the variability and speed at which people with major and mild NCD tap when asked to tap regularly as fast as possible.

Under these conditions, Kluger et al. (1997) identified no difference in terms of produced tempo between patients with MCI and age-matched healthy participants, but found people with mild AD to tap at a lower speed. In contrast, Goldman et al. (1999) did not find an effect of AD on produced fastest tempo. Variability was not taken into account in these studies. Colella et al. (2021) did find tapping variability to increase in people with MCI, but they did not find a difference in tempo between the groups. Taken together, these studies suggest that while a decrease in fastest tempo at which people can tap is only seen in advanced stages of NCD, regularity of fast tapping already appears to decrease in people with mild NCD. This is an interesting parallel to the results found by Roalf et al. (2018), who also observed decreased variability in people with MCI but decreased absolute tempo only with a diagnosis of AD in their SMT task.

To the best of our knowledge, there do not exist any studies comparing people with and without NCD on the ability to tap in a regular fashion as slowly as possible. Since paced tapping at a slow tempo might rely more heavily on WM and attention, we might infer that people with NCD, who tend to be impaired in these domains, might speed up and/or tap with a higher variability when instructed to keep a regular pace as slowly as possible, a prediction that remains to be tested.

Paced Tapping

Synchronization Without Continuation

The performance of tapping along with an auditory metronome has been investigated in people with NCDs in few studies. There might be several reasons for this, but we presume that many of the tasks described in the last few sections could not have been conducted in the same fashion with people with NCDs, especially in groups of patients with major NCD. In this group, particular attention must be paid to avoid stressful, unpleasant, artificial, and invasive laboratory situations. The listening and movement production tasks described in the previous sections might not be suitable for this patient group, and instead research with multimodal stimuli that creates a social or quasi-social situation might be conducive here (Desmet et al., 2017; Lesaffre et al., 2017). An example of this is the paradigm we described in Ghilain et al. (2020a,b), and Hobeika et al. (2021) in which participants were instructed to tap along with music or a regular metronome (IOI = 800 ms) while a musician, either seated across from the participant or projected onto a life-sized screen, vocalized and tapped along with the same stimulus. Under these conditions, benefitting from the presence of a musician, no differences in asynchrony or variability were found between people with and without NCD (see **Table 4**). It must be mentioned that the patients in this study were recruited from a day hospital rather than an inpatient care facility, so they might reflect a relatively independent and mildly impaired NCD group. Their average MMSE score of 20 was just on the fringe between mild and moderate cognitive impairment (Folstein et al., 1983), so we cannot exclude the possibility that a sample of more heavily cognitively impaired patients would show deficits in tapping performance compared to healthy older adults. The lack of effect of NCD might also be explained by other methodological variables, such as the use of only one tempo (close to elderly people's SMT, see **Table 1**) or the impact of social entrainment related to the presence of a partner during the task. Since this paradigm is adapted to people with major NCD, it would be interesting to have a group of more cognitively impaired people perform this task.

Besides this, there do not exist many studies evaluating SMS with complex auditory (musical) stimuli, although, as we argued in Section "Synchronization Without Continuation," it is not only interesting to directly compare SMS to metronomic sequences and SMS to music, due to the presumably different mechanisms involved in beat extraction, but providing musical stimuli can also be of particular value in creating an experimental situation that will make people with NCDs feel comfortable and that has some ecological validity.

One study that did uncover NCD-related differences in SMS was that by Henley et al. (2014). In this study, participants with different variants of frontotemporal dementia and AD synchronized with a metronome at an IOI of 1,500 ms. This study did not find differences in accuracy but higher variability in participants with behavioral variant frontotemporal dementia, but not in participants with other variants of frontotemporal dementia or AD, compared to healthy age-matched adults.

Synchronization–Continuation

Bangert and Balota (2012), whose study was mentioned in Section "Synchronization–Continuation" about healthy aging, had their participants tap at a rate of 500, 1,000, and 1,500 ms, after the metronome stopped. Besides comparing the performance of young and healthy old participants, they also compared the latter group's performance to that of people with very mild (mean MMSE = 27) and mild dementia (mean MMSE = 24). At the interval of 500 ms, they identified no group differences in terms of variability or accuracy (see **Table 4**). At 1,000 ms, people with dementia tapped with a greater variability but at the same accuracy as their healthy counterparts, whereas at 1,500 ms both consistency and accuracy were reduced in

TABLE 4 | Studies investigating paced tapping in people with and without neurocognitive disorders.

Study		Fast tempo (<350 ms)		Comfortable tempo		Slow tempo (>1,000 ms)	
		IOI	NCD effect	IOI	NCD effect	IOI	NCD effect
Bangert and Balota (2012)	Consistency		–	500 ms/1,000 ms	NCD < healthy**[b]	1,500 ms	NCD < healthy*
	Accuracy				No diff.		NCD < healthy**
Carment et al. (2018)	Consistency	333 ms	NCD < healthy***	500 ms/1,000 ms	No diff.		–
	Accuracy		No diff.		No diff.		
Duchek et al. (1994)	Consistency		–	550 ms	No diff.		–
	Accuracy				No diff.		
Ghilain et al. (2020a)	Consistency		–	800 ms	No diff.		–
	Accuracy				No diff.		
Henley et al. (2014) synchronization without continuation	Consistency			–		1,500 ms	NCD < healthy*[a]
	Accuracy						No diff.
Synchronization–continuation	Consistency						NCD < healthy*
	Accuracy						NCD < healthy*[a]
Martin et al. (2017)	Consistency		–	*Determined by SMT task*	NCD < healthy*		–
	Accuracy				No diff.		
Nichelli et al. (1993)	Consistency		–	1,000 ms	NCD < healthy***		–
	Accuracy				Healthy < NCD*[c]		

For simplification, paradigms using synchronization without continuation and synchronization–continuation are reported together here. IOI, inter-onset interval; NCD, neurocognitive disorders; SMT, spontaneous motor tempo.

[a]*Behavioral variant frontotemporal dementia, but not Alzheimer's disease (AD).*

[b]*At 1,000 ms, but not at 500 ms.*

[c]*AD patients were slower than elderly controls, but since elderly controls tended to underestimate the target interval, AD patients' responses were actually more accurate.*

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

cognitively impaired people. These effects were stronger in people with mild compared to very mild dementia. Complementing these findings, Carment et al. (2018) found unimpaired performance with MCI and AD (mean MMSE = 22) at tapping rates of 500 ms and 1,000 ms, but increased variability at the most rapid tempo of 333 ms. Duchek et al. (1994) employed an IOI of 550 ms and found merely a non-significant trend toward higher variability. Nichelli et al. (1993) did not test their participants at shorter intervals, but found AD patients' variability to be larger than healthy participants' at an interval of 1,000 ms, corroborating findings of Bangert and Balota (2012). Along similar lines, Henley et al. (2014), in a synchronization–continuation task at 1,500 ms, found lower accuracy (speeding up) and greater variability in people with behavioral variant frontotemporal dementia, and greater variability in people with AD compared to healthy participants. Based on these studies, it appears that ITI and/or variability in people with NCD are only impacted at relatively long or relatively short intervals, presumably due to an impacted cognitively controlled timing system. However, it is important to point out that the participants in all these studies had on average very mild or mild NCDs.

In contrast, the patients in the study by Martin et al. (2017) tapped with a higher variability than healthy controls, even at a comfortable rate (in this study, the synchronization–continuation task was performed at a rate that depended on their SMT in the preceding spontaneous tapping task; see Section "Spontaneous Motor Tempo"). The apparent discrepancy between this study and the ones mentioned before might be explained by degree of impairment: The patients in study of Martin et al. (2017) had an average MMSE of 19, which indicates moderate cognitive impairment and which was lower than the MMSE scores reported in any of the studies mentioned above. Taken together, these results suggest that SMS performance in people with mild NCD might decline only at relatively long or short tempi, whereas in more severe cognitive impairment, people might tap less precisely even at tempi that are close to their natural speed. Nonetheless, more research about timing abilities in people with moderate or even severe cognitive impairment is needed.

Conclusion: Sensorimotor Synchronization in Neurocognitive Disorders

Overall, there is not a lot of evidence suggesting that tapping at a comfortable rate reveals differences between people with and without NCD. On the other hand, tasks requiring regular tapping as fast as possible have demonstrated increased variability even for people with mild NCD and increased variability as well as slower tapping in people with major NCD. The fact that changes in variability during unpaced tapping are visible even in people with mild NCD are relevant in terms of using motor tasks as a diagnostic tool: While motor speed might only reliably identify people with major NCD, tapping variability could be used to identify people who are at a risk for developing a more serious impairment. Indeed, in MCI, motor impairments are predictive of developing AD (Aggarwal et al., 2006; Ghilain et al., 2020a).

Presently, there is little research studying the effect of cognitive impairment on performance in simple tapping (synchronization without continuation) tasks, but the extant literature suggests that people with frontotemporal NCD might tap less precisely than AD patients and healthy controls at a tempo of 1,500 ms. More research is needed with more different tempi and different levels of cognitive impairment. More commonly, synchronization–continuation studies have been used, and suggested that people with NCD might speed up and show increased variability at slow IOIs from around 1,000 ms, as well as show increased variability at short IOIs below 500 ms. There is some suggestive evidence that even at a comfortable rate, people with a moderate or severe NCD might tap less precisely. Etiology of the NCD may play a role, with a possible interaction between tempo and type of NCD, but more research is needed with various groups of patients with NCD due to different causes, and different levels of impairment.

In short, there is a need for more research investigating SMS abilities in people with moderate and severe cases of NCD. At the same time, however, designing tasks adapted to people with NCD is not trivial: a great deal of effort has to be done to ensure people understand the instructions and to create experimental paradigms that are not stressful, invasive, or unpleasant to the participants. With the existing research, differences between people with and without NCD must be evaluated critically: It is important to verify that they tap into the mechanisms a study claims to test, or whether observed differences may reflect differences in motivation, comfort, or having well understood the instructions. Finally, a fruitful avenue of research would be more studies using musical stimuli of different levels of rhythmic complexity, not only to test the ability to infer and maintain an implicit beat, but also to create a situation that is engaging and motivating, ideally involving a social or quasi-social element resembling real-life musical interaction (Desmet et al., 2017; Lesaffre et al., 2017; Ghilain et al., 2020a,b; Hobeika et al., 2021).

FUTURE DIRECTIONS

To move forward, we suggest the following methodological considerations when conducting research about SMS abilities in healthy aging and NCDs. First, it is useful to employ designs that compare healthy young, healthy old, and cognitively impaired old participants in the same study, in order to disentangle effects of age and of neurodegenerative disorder. A few studies discussed here have done that (Bangert and Balota, 2012; Carment et al., 2018), but most have not. Second, the literature reviewed here suggests that age effects on SMS abilities may not be linear, so it is particularly important to include sufficient amounts of participants from the latest decades of life. Third, likewise, with regard to NCDs, etiology (AD, vascular NCD, frontotemporal NCD, etc.) and severity seem to play important roles when investigating their effects on SMS. We are aware of only one study that compared people with different types of NCDs (Henley et al., 2014). In terms of severity, it is valuable to compare people with major and mild NCDs, or to define neurocognitive impairment as a continuous variable, measured by rating scales, such as the MMSE, mentioned above, the Montreal Cognitive Assessment (Nasreddine et al., 2005), or the Mattis Dementia Rating Scale (Mattis, 1976). These scales need not be mutually exclusive but can be complementary instruments of evaluation of cognitive state (Freidl et al., 1996; Cullen et al., 2007; Arevalo-Rodriguez et al., 2013). Fourth, when conducting research with people with NCDs, particular attention should be paid to creating a pleasant and stimulating atmosphere and to avoid stress. Otherwise, it cannot be excluded that observed between-group differences are reflective of differences in motivation, discomfort, or comprehension of the instructions, rather than sensorimotor abilities. Finally, musical training should always be probed, to ensure that different participant groups are matched on this variable but also to test the possible rehabilitative or neuroprotective effect of music engagement in old age and NCD.

As we mentioned, it will be interesting to conduct more studies on SMS to music. SMS is about predicting, extracting, and maintaining a representation of a beat; however, this beat is not a physical entity but a cognitive percept that needs to be extracted, a process that might be quite different for real music than for isochronous metronomic stimuli. The question of whether aged people and/or people with NCDs have a particular difficulty or a particular ease synchronizing with a musical rhythm is at present still an open one.

Furthermore, this review discussed tasks in which participants produced rhythmic responses, but there also exists task assessing beat perception in a purely perceptual fashion, such as the Harvard Beat Alignment Test (Fujii and Schlaug, 2013) and some subtests of the BAASTA (Dalla Bella et al., 2017b). Moreover, rhythm production and perception can independently be impacted (Bégel et al., 2017). It would be interesting to test rhythm perception abilities specifically in elderly people with and without NCDs.

Since the focus of this review was SMS to simple isochronous or musical rhythms, we did not touch upon the topic of error correction. Although error correction is an ever-present process in SMS without which one would eventually become out of sync (Vorberg and Wing, 1996), it is usually examined by introducing perturbations of the IOI and testing how quickly and efficiently participants adapt their own tempo to them. Generally, a difference is made between phase correction and period correction, The former refers to an automatic, often unconscious mechanism of adaptation to subtle perturbations that is associated with primary and secondary somatosensory cortical activity, whereas the latter refers to a mechanism correcting for more obvious changes in the temporal sequence that depends on attention and awareness and involves brain networks, such as the basal ganglia, prefrontal, medial frontal, and parietal regions (Thaut et al., 1998; Repp, 2001; Praamstra et al., 2003; Repp and Su, 2013; Ross et al., 2018). It is conceivable that phase and period correction would be differently influenced by aging and NCDs. A study (Repp and Keller, 2004) that manipulated attention by introducing a concurrent mentally taxing task found period correction to be affected by this reduction in available attentional resources, whereas period correction was not. Furthermore, in a recent study with musicians (Versaci and Laje, 2021), attention was guided in a more explicit way by directing some participants' attention to temporal features of the task, in turn yielding higher accuracy and more efficient resynchronization after a perturbation of a relatively large size, probably employing period correction mechanisms. It can be conjectured that very old and old people would be especially impaired in tapping along with sequences containing tempo changes, particularly those large enough to depend on period correction mechanisms, and, in cerebral terms, on frontal and parietal integrity.

GENERAL CONCLUSION

Neurocognitive disorders, as well as healthy aging, are often associated with a decline in memory, attention, and executive function. Less often, we tend to think of sensorimotor dysfunction as a prototypical symptom of physiological and pathological aging, except in the case of Parkinson's disease. Restricting our review to the other etiologies of NCDs, we have indeed observed many examples in this review in which no clear difference on SMS performance emerged between young, healthy old, and/or cognitively impaired old people. However, SMS abilities are a complex set of skills with different subcomponents that may be differently affected by aging and NCDs, and substantial heterogeneity exists between and within different NCDs, as well as between aging brains in general.

In some cases, there is clear evidence for decline on SMS tasks for elderly people and/or people with NCDs. Specifically, SMS ability might be especially impaired above the age of around 75 and for people with moderate and/or severe NCDs. People with frontotemporal NCDs might particularly struggle with SMS tasks, although research comparing different NCD etiologies is sparse. These effects might be augmented with stimuli whose tempo is further away from a person's comfortable, natural tempo (i.e., IOIs faster than around 300 ms and slower than around 1,000 ms). The exact instructions, protocol, and trial length might play a role, especially in spontaneous motor tasks. Musical background might also modulate the effect of aging and NCDs on SMS abilities, and cognitive load might have a different effect on performance for the different groups. More specifically, due to rewiring and compensation mechanisms, SMS, usually a quite spontaneous process requiring little cognitive resources, might become heavier in cognitive load and interfere with other concurrent tasks. Rhythmic complexity might be relevant although our analysis was restricted to two ends of the extreme: simple, isochronous rhythms, and music, the latter of which merits more attention than it is currently given. To fully understand late-life development of sensorimotor processes, more research is needed that reflects the wide array of types of auditory stimuli as well as the diversity of aging brains.

The observation that slightly younger elderly people and people with mild NCDs tend to be relatively unimpaired in synchronizing particularly at tempi of around 500 and 1,000 ms is a strong argument for the use of music-based interventions. Musical tempi tend to lie within this range, and capitalizing on this relatively preserved skill could be a fruitful approach. The stimulation of motor systems in older adults across different levels of cognitive impairment may not only improve their sense of rhythm, but lead to emotional and cognitive benefits as well as improvements in the ability to predict the unfolding of events in the environment, leading to improved communication and reduced social isolation.

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AS, LH, and SS: conceptualization. AS: writing the original draft. LH and SS: review, editing, and supervision. DH-G: review. All authors contributed to the article and approved the submitted version.

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Chapter 3

Bridging the gaps

In the preceding literature review, we summarized the current understanding of sensorimotor synchronization (SMS) in the context of aging and neurocognitive disorders (NCD). Despite the critical role of auditory-motor abilities, and despite the promise of employing rhythm in music-based interventions to improve the quality of life of older adults and those with NCD, research on SMS skills remains scarce, particularly with respect to NCD. Our review highlighted that while basic SMS abilities needed for synchronization with isochronous sounds are generally well-preserved in aging and NCD, problems may arise with slower tempi, complex rhythms or synchronization-continuation paradigms, likely due to their increased reliance on working memory and attentional resources.

Error correction and adaptation to tempo changes

Another fundamental mechanism implicated in SMS, and one that has been underexplored in the context of aging and NCD is error correction. Timekeeping in SMS implies the generation of a target interval that provides periodic events and triggers motor responses. Even if this interval matches the sequence tempo, there are random fluctuations which would accumulate if there was no error correction, which is thus an ever-present mechanism without which one would gradually become out of sync, even in the case of tapping with an isochronous stimulus without tempo changes (Repp, 2005; Vorberg & Wing, 1996; Wing & Kristofferson, 1973). However, the role of error correction in SMS can be increased by introducing tempo changes into a target sequence and analyzed as people adapt to this perturbation. Adapting to tempo changes requires attentional and cognitive resources (Repp & Keller, 2004) and likely depends on the integrity of structures like the medial frontal cortex, including the supplementary motor area (Praamstra et al., 2003). In a study exploring SMS to real musical sequences with expressive timing (i.e., fluctuating beat regularity), a role of working memory was identified in synchronizing with these sequences (Colley et al., 2018). The authors argued that working memory would enable fluid shifts in action planning and execution, specifically in updating temporal intervals. While expressive timing is not the same as sudden tempo changes, it is plausible that working memory would be involved for the same reasons. Additionally, a mechanism that is likely involved in adapting to tempo changes is cognitive flexibility. It describes the ability to flexibly shift between mental sets and strategies (Friedman et al., 2006). In the context of SMS to tempo-shifting sequences, cognitive flexibility may allow individuals to adjust their timing and coordination to changes in the rhythmic structure. Cognitive flexibility has been found to be compromised in people with NCD (Garrett et al., 2004; Kowalczyk et al., 2001), so it is likely that people with NCD, who have deficits in working memory and cognitive flexibility, will exhibit a particular difficulty in adapting to tempo changes.

Methodological considerations

While we were interested in the effects of tempo stability and beat saliency on SMS, we did not aim to introduce any particular difficulty by choosing tempi that were far from people's comfortable range. An individual's comfortable tempo refers to their preferred or natural rate of rhythmic motor activity, and it can be determined by assessing people's spontaneous motor tempo (SMT). The rate at which people spontaneously tap is thought to be reflected in other motor functions such as gait or speech. It has been demonstrated that people generally display the highest level of synchronization performance at stimulus tempi that are close to a person's SMT (McAuley et al., 2006; Scheurich et al., 2018; Tranchant et al., 2022).

Recruitment and participant characteristics

For a comprehensive understanding of the impacts of age, NCD, and cognitive abilities on SMS, we recruited participants at a geriatric hospital where the expected population was relatively diverse in terms of all these factors; the age of the patients of Lille University Hospital, the place of recruitment, spanned people from their early sixties to their nineties. Additionally, they represented a spectrum from older adults with no cognitive impairments or light memory problems that were deemed normal for their age group, to people with major NCD of different origins.

Stimulus creation

Past research has demonstrated, in people with moderate to severe NCD, significant positive engagement with live music, an effect not observed with pre-recorded music (Holmes et al., 2006). However, providing in-person live music is not always feasible, in interventions as well as in fundamental research. Therefore, it is worth exploring paradigms that strike a balance between the two extremes described in Holmes et al.'s (2006) study (i.e., live music provided by a musician, and pre-recorded music playing in the background). Building on this rationale, studies were conducted at our lab in which participants engaged in an SMS task while seated across from either a musician or a video recording of the same musician, who tapped along with the same stimulus (Ghilain, Hobeika, Lesaffre, et al., 2020; Ghilain, Hobeika, Schiaratura, et al., 2020; Hobeika et al., 2021). Even in the condition with only a video of the musician, participants were sufficiently stimulated to move and engage in the task. In fact, SMS consistency was even higher when tapping with the virtual partner.

In keeping with this approach, for the studies described in **Chapters 4 and 5**, I created bimodal stimuli by filming the same musician synchronizing with the auditory stimuli, during which I meticulously assessed his performance to ensure minimal asynchrony and optimal consistency. To be precise, I had the musician practice the tapping extensively at home before the day of recording. During the video recordings, I also presented visual prompts (arrows pointing up or down) preceding each acceleration or deceleration (in those trials that contained tempo changes). He was then filmed doing eight rounds of all trials (64 video recordings) and for every trial, I assessed his performance by calculating mean asynchrony of his taps relative to the beats and coefficient of variation of asynchrony. Finally, per type of temporal structure (see Figure 1 in **Chapter 4** for an illustration of different types of trials), I selected those trials in which the musician demonstrated the lowest asynchrony and the lowest coefficient of variation, a measure of synchronization consistency, and I matched the visual content of those videos with the audio track for the originally created stimuli.

However, for the final experimental study (**Chapter 7**) I presented only auditory stimuli. Indeed, it was crucial to test synchronization using a purely auditory stimulus While many real-life interactions involve multimodal stimuli, using a unimodal auditory stimulus was essential to ensure that our conclusions pertained to how people synchronize with sound. With video stimuli, it is challenging to discern whether people synchronize with what they hear, what they see, or both.

Cognitive functions underlying sensorimotor synchronization

The first experimental study (detailed in **Chapter 4**) was largely built on the assumption that certain cognitive abilities, such as working memory and attention, may be impacted in NCD and, by being involved in SMS, would manifest in lower performance in this patient group. However, any conclusion with regards to specific cognitive mechanisms was speculative, since the only measure of cognitive status was the mini-mental state examination (MMSE), a global screening tool for symptoms of NCD (Folstein et al., 1983). We therefore conducted the study described in **Chapter 6**, which in fact includes data collected prior to the onset of this PhD, about a part of which three articles have previously been published (Ghilain, Hobeika, Lesaffre, et al., 2020; Hobeika et al., 2021, 2022). Since a large part of this patient pool underwent a full neuropsychological screening, we analyzed the SMS data to establish links between sensorimotor performance and specific cognitive functions, namely, short-term memory, working memory, and inhibition.

Finally, we designed the final experimental study (described in **Chapter 7**) through which we captured in more detail the processes related to SMS, beat perception, motor initiation, and how each of them is linked with cognitive abilities. As mentioned in the preceding literature review, it is important to include measures of beat perception in addition to tapping tasks. While rhythm perception and production tend to covary (Dalla Bella et al., 2017; Fujii & Schlaug, 2013; Iversen et al., 2008; Puyjarinet et al., 2017), there is evidence of dissociation; some studies have found impaired synchronization with preserved beat perception (Provasi et al., 2014; Sowiński & Dalla Bella, 2013) and vice versa (Bégel et al., 2017). This final study was designed to examine SMS, unpaced motor variability, and beat perception. This was achieved by using stimuli with varying levels of beat clarity, assessing unpaced motor variability by including spontaneous tapping variability, including the Beat Alignment Test (Dalla Bella et al., 2017; Iversen et al., 2008) to probe beat perception, and including a Go/No-go test (Dubois et al., 2000) as a measure of inhibition control.

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Chapter 4

Sensorimotor impairment in aging and neurocognitive disorders: beat synchronization and adaptation to tempo changes

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Sensorimotor Impairment in Aging and Neurocognitive Disorders: Beat Synchronization and Adaptation to Tempo Changes

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Abstract.
Background: Understanding the nature and extent of sensorimotor decline in aging individuals and those with neurocognitive disorders (NCD), such as Alzheimer's disease, is essential for designing effective music-based interventions. Our understanding of rhythmic functions remains incomplete, particularly in how aging and NCD affect sensorimotor synchronization and adaptation to tempo changes.
Objective: This study aimed to investigate how aging and NCD severity impact tapping to metronomes and music, with and without tempo changes.
Methods: Patients from a memory clinic participated in a tapping task, synchronizing with metronomic and musical sequences, some of which contained sudden tempo changes. After exclusions, 51 patients were included in the final analysis.
Results: Participants' Mini-Mental State Examination scores were associated with tapping consistency. Additionally, age negatively influenced consistency when synchronizing with a musical beat, whereas consistency remained stable across age when tapping with a metronome.

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Conclusions: The results indicate that the initial decline of attention and working memory with age may impact perception and synchronization to a musical beat, whereas progressive NCD-related cognitive decline results in more widespread sensorimotor decline, affecting tapping irrespective of audio type. These findings underline the importance of customizing rhythm-based interventions to the needs of older adults and individuals with NCD, taking into consideration their cognitive as well as their rhythmic aptitudes.

This study was registered at clinicaltrials.gov (NCT04146688).

Keywords: Aging, Alzheimer's disease, auditory perception, dementia, music, neurodegenerative diseases

INTRODUCTION

Neurocognitive disorders and music-based interventions

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

Sensorimotor synchronization

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

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

How do age and neurocognitive disorders impact sensorimotor synchronization?

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

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

Several studies have indicated that SMS abilities tend to be relatively preserved in individuals with NCD when instructed to tap along with a metronome set to a comfortable tempo [31]. However, differences were observed when participants had to continue tapping after an external sequence had ended [22, 32] or when the target rate deviated substantially from their comfortable tempo [22, 33, 34], manipulations likely to engage working memory and attention. However, a recent study by Hobeika et al. [35] revealed a decline in performance among individuals with major NCD in tapping even at a comfortable rate with a metronome and with music, and a positive relationship between consistency during metronome tapping and participants' score on the Mini-Mental State Examination (MMSE), a brief screening tool for assessing NCD [36]. These different results may be explained by the severity of NCD in Hobeika et al.'s study (their NCD group had a mean MMSE of 15.5, which was lower than in the other studies). However, definite conclusions cannot be drawn from Hobeika et al.'s study because they pooled together participants who were tested under different conditions, which emphasizes the need for the current study, investigating the impact of NCD severity under homogeneous testing conditions.

As previously mentioned, synchronization with music requires extracting a beat from a complex and abstract auditory signal, with musical events occurring on nested timescales, requiring efficient allocation of attention over time for successful beat extraction [37]. It may be that in healthy aging people, or mild forms of NCD, tapping with a metronome may be a largely automatic process, and only when tapping with music, or in cognitively challenging paradigms are attention and working memory processes recruited, leading to a decline in performance. However, for people at more severe stages of NCD, attention and working memory are needed even to synchronize at a comfortable pace with a metronome. Indeed, some research has demonstrated increased use of non-motor regions during simple motor tasks in NCD, at least in AD [38, 39], indicating that with increasing severity of the disease, individuals employ other domain-general brain networks during SMS, reflecting a shift to more effortful and less automatic processing of rhythm, and potentially lower performance due to increasing competition for limited cognitive resources. It is possible that individuals in moderate to severe stages of NCD may require more attention and working memory even for tapping with simple metronomic sequences, and may be more impaired in these cognitive abilities, resulting in a general sensorimotor impairment manifested by reduced consistency when tapping to any regular stimulus, be it a metronome or music.

Similar to synchronization-continuation tapping and tapping at tempi far from one's comfortable rate, tapping with a sequence containing tempo changes may particularly involve attention and working memory [18]. A particular impairment in SMS with tempo changes has already been demonstrated in other clinical populations, namely, people with traumatic brain injury [40], autism spectrum disorder [41], basal ganglia pathology [42], and cerebellar lesions [43], and has been explained in terms of attention-dependent temporal processing. Since attention is greatly impaired in people with NCD [44], the ability of people with NCD to adapt their tempo when encountering tempo changes may be compromised, due to an imprecise representation of temporal structure and inefficient allocation of attention over time [42]. Finally, a decline in cognitive flexibility found in people with NCD [45, 46] may present another contributing factor to their potential disadvantage in adaptation to tempo changes. To our knowledge, there does not exist any research examining the effect of NCD on tempo adaptation in SMS. It is important to investigate this aspect, as adaptation to tempo changes can serve as a model for understanding how individuals interact with a dynamically changing environment in general.

The current study

The aim of the current study was to test the effects of age and NCD severity on SMS to metronomes and to music with and without tempo changes. In this context, we examined SMS skills, with particular emphasis on the impact of tempo changes by introducing sudden accelerations and decelerations every 15 s in half of the trials, and computing consistency and asynchrony. The difficulty in this task should come only from the changes in tempo, rather than presenting participants with inherently difficult tempi for synchronization. To achieve this, we selected base tempi that closely aligned with the typical spontaneous motor tempo reported in the literature for older adults [21, 25] and we confirmed this by assessing individuals' spontaneous tempo. In traditional SMS paradigms, participants typically tap their finger or hand to an auditory regular beat. However, when applying such paradigms to individuals with NCD, particularly in advanced stages, special consideration is required to avoid stressful, unpleasant or artificial laboratory situations, as they might find it difficult to cope with such conditions, and they may experience difficulties in retaining and following instructions, especially in longer experiments. For these reasons, tasks with multimodal stimuli, creating a quasi-social situation, may be conducive [47, 48]. Additionally, people, including older adults with NCD, might actually perform better when synchronizing with a video than with another person [14, 49]. We recently developed and validated an experimental setup tailored to elderly individuals [14, 49, 50] and continue its use to present stimuli bimodally (audio plus video). Using this experimental design and assessing a group of older adults exhibiting a range of ages and varying levels of cognitive impairment created an optimal setting for examining the distinct impacts of both age and NCD on sensorimotor synchronization.

Firstly, we expect a global impairment in SMS with increasing NCD severity. Specifically, we expect that MMSE score will have a negative impact on tapping consistency. Second, we hypothesize that consistency will be lower in trials with a shifting tempo compared to those with a stable tempo. Third, we predict an interaction between the presence or absence of tempo changes and MMSE score, such that the reduction in consistency in the shifting condition will be more pronounced in individuals with a lower MMSE score, probably due to declines in attention, working memory, and cognitive flexibility. Fourth, consistent with previous research, we expect lower consistency when individuals synchronize their movements with music compared to a metronome [12–14]. Fifth, due to increased reliance on beat induction with music and decreased attentional capacities with aging, we expect consistency to decrease with age when individuals tap with music, but to a lesser extent (or not at all) with a metronome. Sixth, and finally, we hypothesize that asynchrony will be lower (more negative) in the metronome conditions compared to music [7, 8, 12–14, 51].

MATERIALS AND METHODS

Participants

A total of 61 patients were recruited at the geriatric day hospital *Les Bateliers* (Lille University Hospital, France), during a scheduled consultation related to memory problems or falls. Inclusion criteria included age between 60 and 99, right-handedness and native or near-native fluency in French. Patients were ineligible for participation if they had Parkinson's disease, other motor disorders or paralysis, or uncorrected hearing or vision problems. Patients' data were excluded from analysis if they did not finish the experiment. Most patients were diagnosed with major or minor NCD, whereas a minority of patients were attested subjective memory complaints without evidence of NCD. This diagnosis was made by a geriatrician and based on DSM-5 criteria [1]. However, in this study, we assessed cognitive impairment as a continuous variable using the MMSE. After ten exclusions (seven who withdrew from the study during the experiment, one due to technical problems, one who tapped in a seemingly random fashion in all trials as indicated by Rayleigh's test [52], and one whose MMSE score of 14 was an outlier; 3 SDs below the mean), 51 patients were included in this study. The data were collected between November 2021 and July 2022. The study was approved by the local Ethics Committee (Comité de Protection des Personnes, Sud-Est VI, France; No. 2017-A03543-50) and by the Commission Nationale de l'Informatique et des Libertés, registered at clinicaltrials.gov (NCT04146688). All patients provided written informed consent for their participation in accordance with the Declaration of Helsinki.

Materials

Experimental apparatus

The experimental set-up included a chair with a tablet attached to the right armrest on which the patient tapped using a ball-like probe they held in their right hand [47, 48]. A life-sized screen (158 × 92 cm) and a pair of loudspeakers were placed in front of the patient at a distance of 230 cm. A video of a musician tapping to the simultaneously presented auditory sequence was projected onto the screen during the task in front of the patient. Each patient was tested individually and was separated from the experimenter by a curtain to avoid distraction. Stimuli were presented and responses collected using a program written in MAX/MSP (https://cycling74.com).

Stimuli

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

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

The musical and metronomic sequences were manipulated to conform to one of four temporal patterns (Fig. 1): A stable IOI of 674 ms (A), a stable IOI of 741 ms (B), or a sequence in which the tempo shifted every 15 seconds between the two, starting either at 674 ms (C) or starting at 741 ms (D). Ableton Live was used to render the musical stimuli from the MIDI versions using their in-house instruments, to create the metronomic stimuli and to perform the tempo manipulations. The visual part of the audio-visual stimuli was created beforehand by filming the musician who sat in the position of the participants, listened to the musical stimuli and tapped along. An analysis of the musician's tapping consistency and asynchrony during the recording of these videos indicated very good performance and minimal error (see Supplementary Table 1).

Procedure

The experiment started by orally administering a musical expertise questionnaire, which inquired about participants' musical training, listening habits, and engagement with music (only the total score is reported here). Then, short forms of the Geriatric Depression Scale [53] and the Geriatric Anxiety Inventory [54] were orally administered. Next, each patient performed a brief spontaneous motor task by tapping as regularly as possible for 31 taps (30 inter-tap intervals; ITIs), at their preferred, comfortable tempo.

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

Data analysis

Calculation of SMS variables

For the 30 intervals produced during the spontaneous motor task, we calculated mean ITI and CV (standard deviation divided by mean) of ITI. In the paced tapping task, as we mentioned above, the tempo either remained stable or shifted every 15 s. We therefore computed consistency and asynchrony per 15-s segment using circular statistics [55] with the CircStat

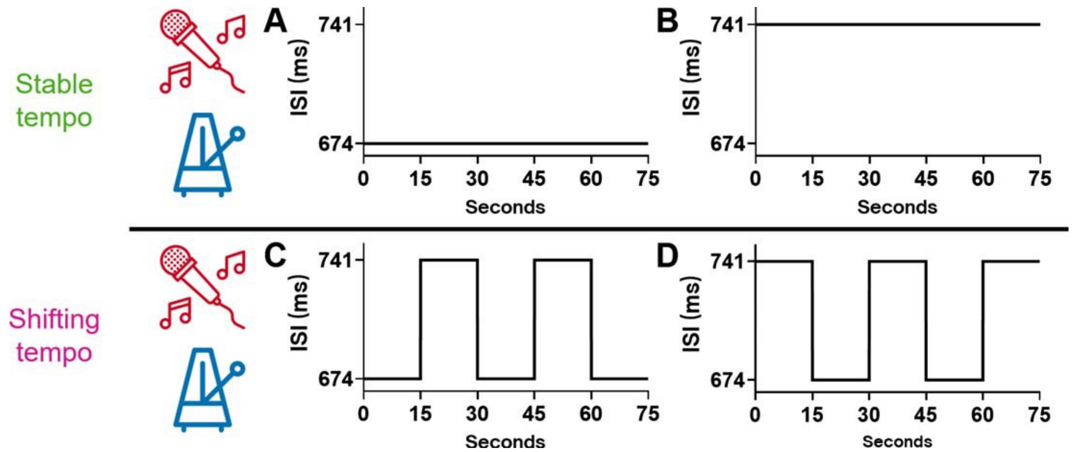

Fig. 1. Types of audio and temporal structures used in the experimental trials. Using two types of audio (music and metronome) and tempi corresponding to four temporal patterns (A, stable tempo of 674 ms; B, stable tempo of 741 ms; C, shifting tempo starting at 674 ms; D, shifting tempo starting at 741 ms) resulted in eight different experimental trials.

toolbox [56] in MATLAB [57]. We opted for circular analysis of synchronization data as this allowed for a robust analysis even in the case of missing or superfluous taps, as asynchronies and their variability can be computed without necessarily attributing each response event to a particular beat [58]. In a given trial, ms in an inter-onset interval (IOI) are converted into degrees on a circular scale going from –180° to +180°. The beat's onset is at 0°, the time a participant would be expected to tap. An angle of 180° would indicate a participant tapping in antiphase. Vectors were averaged to obtain a mean resultant vector $\vec{R}$ [55, 56] allowing for the calculation of synchronization consistency and asynchrony. Consistency is represented by the length of the vector $\vec{R}$ and ranges from 0 to 1, where 1 corresponds to perfect consistency (all taps occurred with the same delay to the beat) and 0 describes a situation where taps were randomly distributed between the beats. Asynchrony reflects the angular deviation (Θ) of vector $\vec{R}$ from 0, which is then transformed back into ms (Fig. 2). Consistency and asynchrony were only analyzed for the segments 2 through 5, as performance in the first segment was not pertinent to us since no tempo change would have occurred in this segment, even in the shifting condition (see Supplementary Figure 1).

Statistical analyses

All statistical analyses were performed in R 4.2.2 using RStudio [59, 60]. We analyzed SMS consistency and asynchrony by conducting mixed-effects models. In the analysis of consistency, fixed effects included the variables audio, tempo stability, age, MMSE, as well as the interactions between audio and age, audio and MMSE, tempo stability and age, and tempo stability and MMSE. The analysis of asynchrony only included audio as a variable of interest since the only hypothesis regarding asynchrony pertained to this variable. In both analyses, we controlled for the effects of gender, years of education, and musical expertise by entering them as additional fixed effects in the model. Finally, participant was entered as a random effect in both models. In the analysis with consistency as a dependent variable, a generalized linear mixed model with a beta distribution and a logit link was performed using the glmmTMB package [61] in R. For both analyses, we removed segments where asynchrony was lower than –135° or higher than 135°, indicating tapping in antiphase. In the analysis with asynchrony as a dependent variable, we first removed from the analysis segments with insufficient taps (i.e., where the percentage of taps relative to the number of beats was more than 2 standard deviations below the mean). Then, we transformed the variable asynchrony by taking the cubic root of its absolute value and multiplying it with its original sign. This was done to fulfil the assumption of normality of residuals, as asynchrony was right-skewed. Then, we performed a linear mixed-effects model analysis using the lme4 package [62]. Type II Wald chi-square tests were used to test the main effects and interactions. We present effect size by computing f^2, which is considered an appropriate metric of effect size in mixed-effects regression models [63].

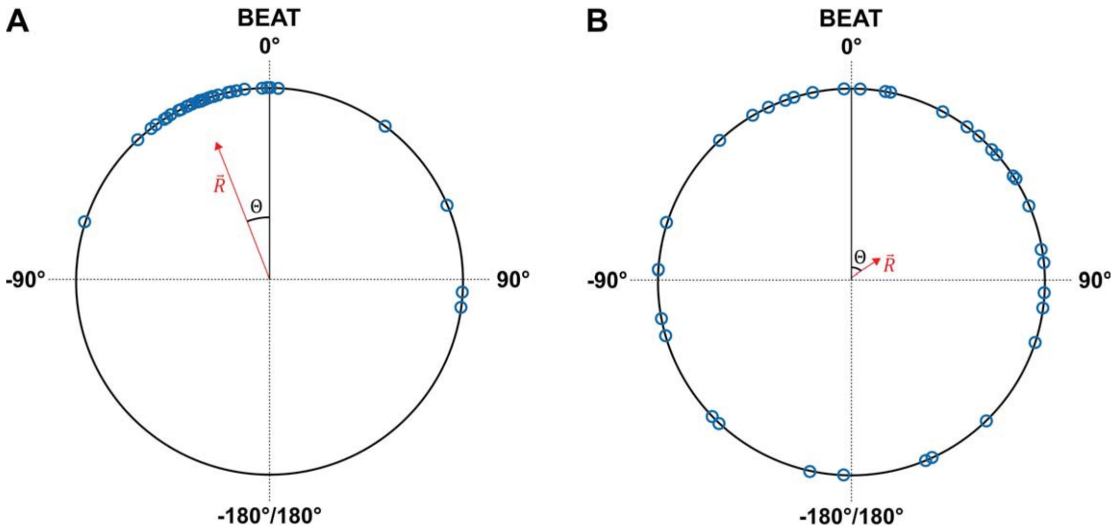

Fig. 2. Two examples of circular synchronization analysis in a given trial. Each inter-onset interval is converted to degrees on a circular scale. The time at which each tap occurs, relative to the beat (= 0 degrees) is then represented by a specific angle on the circle (blue minicircles). The mean vector R summarizes the performance during a 15-second segment. The mean direction (Θ) 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).

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		21 (44%)	
Minor NCD		24 (50%)	
No NCD		3 (6%)	
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.

RESULTS

Participants

Demographic data, including age, gender, education and musical expertise, and clinical data, encompassing diagnosis, MMSE, Activities of Daily Living [64], Instrumental Activities of Daily Living [65], Geriatric Depression Scale, and Geriatric Anxiety Inventory, can be found in Table 1. Of the 21 participants diagnosed with major NCD, nine were diagnosed with AD, two with vascular NCD, 11 with NCD of mixed etiology, and one with NCD of an unknown origin. A distribution of MMSE scores is shown in Supplementary Figure 2. An analysis of variance revealed significant differences in MMSE between groups of people with different diagnoses, $F(2, 1510) = 847.2$, $p < 0.001$. Post hoc

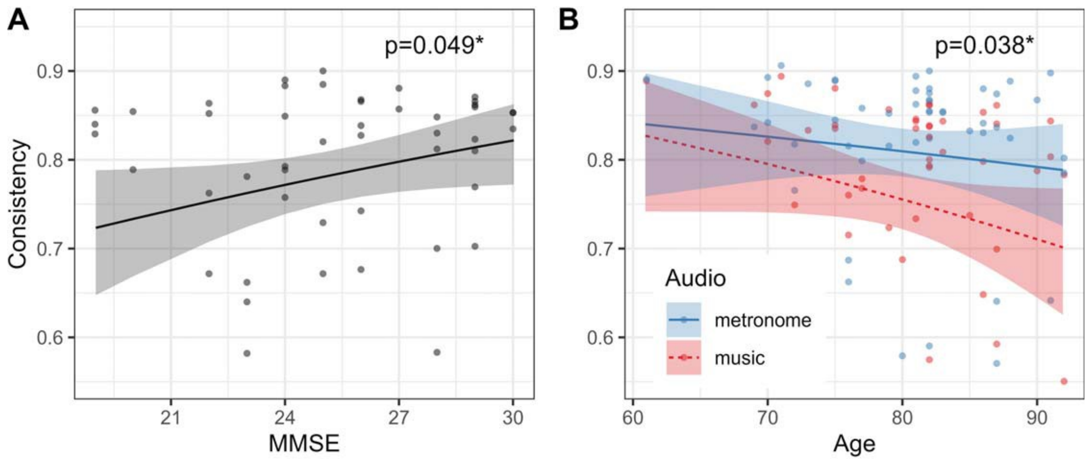

Fig. 3. Effects of MMSE, and of the interaction of audio and age on consistency. A) More cognitively impaired people (i.e., with a lower MMSE score) tapped with a lower level of consistency. B) Consistency decreased with age, but only in the music conditions. MMSE, Mini-Mental State Examination

tests using Bonferroni correction confirmed that the group of people without NCD had the highest average MMSE (M = 29.00, SD = 0.82), followed by the group with minor NCD (M = 25.22, SD = 2.83), and finally, the group with major NCD had the lowest average MMSE (M = 24.51, SD = 3.42). These differences in MMSE scores were statistically significant across all groups (all ps < 0.001). Demographic and clinical data of the seven participants who withdrew from participation during the study can be found in Supplementary Table 2. The participants who did not finish the study were on average older (U = 66.0, $p < 0.01$, Mann-Whitney U test) and had a lower MMSE score (U = 265.5, $p < 0.05$, Mann-Whitney U test) than those who did, whereas the two groups did not differ in terms of gender, diagnosis, education, musical expertise, ADL, IADL, depression, or anxiety (all ps > 0.05). Moreover, all participants who finished the study prematurely were diagnosed with major NCD.

Tapping tasks

Participants' mean spontaneous motor tempo was 715 ms (SD = 468 ms). This confirms that the tempo of the experimental stimuli (674 ms and 741 ms) was within a comfortable range.

The results of the generalized linear mixed model with consistency as a dependent variable are presented in Supplementary Table 3. A main effect of MMSE (Wald $\chi^2 = 3.86$, $p < 0.05$, $f^2 = 0.03$) suggests that more cognitively impaired people (i.e., with a lower MMSE score) tapped with a lower level of consistency (Fig. 3A). Unsurprisingly, a main effect of tempo stability ($\chi^2 = 756.34$, $p < 0.001$, $f^2 = 0.21$) indicates that consistency was higher in trials with a stable tempo compared to those with a shifting tempo. In addition, there was a significant effect of Audio ($\chi^2 = 76.44$, $p < 0.001$, $f^2 = 0.04$), with consistency being higher when participants synchronized with a metronome compared to music. Furthermore, there was a significant interaction of audio and age (Wald $\chi^2 = 4.28$, $p < 0.05$ $f^2 < 0.01$; Fig. 3B). Consistency appeared to decrease with age, but only in the music conditions.

There was also a two-way interaction effect of tempo stability and age on consistency. However, the slopes of the two regression lines were not significantly different from zero (both ps > 0.05) and is unlikely to have practical significance. We therefore report this effect only in Supplementary Figure 3.

The results of the linear mixed model with asynchrony as a dependent variable are presented in Supplementary Table 4. As predicted, the main effect of audio was significant (Wald $\chi^2 = 248.08$, $p < 0.001$, $f^2 = 1.38$), indicating that participants' taps occurred close to the beat when tapping with music, whereas their taps tended to anticipate the beat when tapping with a metronome (Fig. 4).

Finally, we checked for the potential confounding effects (such as tempo and segment) in a supplementary analysis presented in Supplementary Tables 5 and 6. The results revealed that the effects of interest showed no difference with the simplified models presented above.

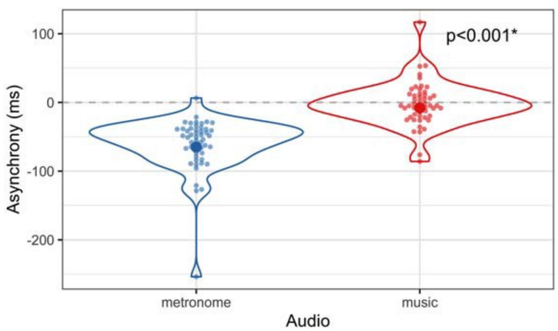

Fig. 4. Effect of audio on asynchrony. In order to fulfil the assumption of multivariate normality, the dependent variable asynchrony was transformed by taking the cubic root of its absolute value and multiplying it with its original sign. However, this figure was created by taking estimated marginal means and standard deviations of a linear mixed model with non-transformed data.

DISCUSSION

The purpose of this study was to investigate the influence of age and NCD severity on SMS performance, quantified as tapping consistency and asynchrony. We were particularly interested in whether different subprocesses of SMS, including beat induction, beat maintenance, and error correction, might be differentially impacted by age and NCD. This differential impact could manifest in age and NCD unequally influencing SMS performance when synchronizing with music versus metronomes, and with tempo-changing sequences compared to sequences with a stable tempo. We demonstrated that tapping consistency decreased with MMSE, providing evidence of the impact of neurocognitive disorders on sensorimotor abilities and thereby confirming our first hypothesis. Not surprisingly, our second hypothesis of a detrimental effect of tempo changes on tapping consistency was also confirmed. Contrary to our third hypothesis, however, the effect of MMSE did not depend on tempo stability. People in general tapped with a lower level of consistency to music than to a metronome, confirming our fourth hypothesis and the results of previous studies [12–14]. Additionally, and as predicted by our fifth hypothesis, we observed a decrease in consistency with age, but only when individuals tapped with musical sequences and not with a metronome. Supporting our sixth and final hypothesis, asynchrony was lower (more negative) in the metronome condition compared to the music condition. Before discussing these results in depth, it is worth noting that participants' mean spontaneous motor tempo of 715 ms is close to what has previously been found in older adults [21, 25]. More importantly, it was squarely in between the two stimulus tempi in the paced tapping task (674 ms and 741 ms). It is therefore reasonable to assume that both tempi were in the range of comfortable rates for our participants.

Effect of NCD severity on consistency

The observed association between MMSE score and tapping consistency is in line with previous findings. A recent study by Hobeika et al [35] also found reduced consistency in people with major NCD compared to those with mild or no NCD, as well as a positive linear relationship between MMSE and consistency during an audio-visual tapping task. However, the latter result was limited to the metronome condition, whereas participants were not impaired with music. Interestingly, in our study, cognitive impairment had a global impact on consistency, affecting tapping with both metronome and music. Perhaps these differences stem from the fact that our study, which included trials with tempo changes, was more sensitive to uncovering NCD-related effects. On the other hand, the effect of NCD severity on tapping to music present here but absent in Hobeika et al.'s study might be attributed to music-induced reward. The motivating and rewarding qualities of music may boost synchronization, resulting in more consistent tapping [66]. Perhaps Hobeika et al.'s stimuli, with original music recordings and sung lyrics, were more rewarding than our MIDI-based stimuli which did not contain lyrics and which were also repeated more often within the same experiment. Perhaps a difficulty in synchronizing to music was offset by enhanced synchronicity related to reward in Hobeika et al.'s study, underscoring the relevance of selecting music for its motivating and rewarding qualities.

The finding of an NCD-related deficit in SMS at a comfortable rate is novel: Some studies have previously shown lower tapping consistency in people with NCD, but only when they had to continue tapping after an external sequence had ended [22, 32] and/or when the tempo they synchronized with was far from their comfortable tempo (i.e., slower [22, 34] or faster [33]). We hypothesized that the tempo-changing manipulation would be particularly difficult for more cognitively impaired people and that MMSE and tempo stability would therefore interact, but this effect was not observed in this study. It may be that the current task and its analysis pipeline, examining consistency by 15-s segments, and comparing these segments across conditions, may have been too crude, given that people only take a few taps to adapt to a new tempo [18, 67, 68], at least healthy participants. Additionally, it is possible that the bimodal nature of the task (audio and video) made the task easier, offsetting the difficulty introduced by the tempo changes. Finally, while MMSE was chosen as a predictor variable to capture the full spectrum of cognitive impairment, this may have resulted in reduced statistical power to detect effects, especially interaction effects, than sampling two extreme groups [69]. Additional research on rhythmic synchronization with tempo changes is warranted, as it may provide insights into how individuals generally entrain to regularities and adapt to changes in their sensory environment.

This study, along with another recent study [35], highlights a global deficit in SMS abilities among individuals with NCD. Given the established connection between rhythmic and cognitive abilities, it can be speculated that rhythmic training may confer cognitive benefits. However, the direct transfer of benefits from musical to non-musical domains requires further investigation. There exist other neurological conditions like Parkinson's disease, Huntington's disease, autism spectrum disorder, attention deficit hyperactivity disorder, and dyslexia, where rhythmic deficits are prominent and rhythm-based training may offer advantages beyond the motor realm, such as on communication and executive functions [70–76]. By continuing to study SMS and its links with cognitive abilities, we may get a clearer picture of what processes may inadvertently be stimulated through rhythm-based interventions, to slow down symptoms in NCD, but also as a preventive strategy in healthy older adults [77–80]. Finally, the current results also suggest that sensorimotor problems could serve as a potential diagnostic marker of NCD, warranting inclusion in the neuropsychological evaluation process, but only as complementary tests among measures of working memory and attention, for which the link with NCD is more established.

Interaction between audio and age on consistency

Another noteworthy result was an interaction effect of audio and age on consistency. Age negatively affected tapping consistency when people synchronized their taps with music, but not with a metronome. This observation offers a more nuanced perspective on past research that found higher consistency when tapping with metronomes compared to music [12–14] and research on the effect of age on SMS which often found null results at least with a comfortable tempo, but which rarely used music material as a stimulus, but rather metronomes [20–22, 24–26, 33, 81] (but see [27, 82]). The current findings, revealing distinct effects of age on tapping to metronomes versus tapping to music, suggest that beat maintenance and beat induction may be affected differently. Perhaps older adults experience greater impairment in beat induction processes, which are crucial for tapping with music, whereas they retain their ability in the automatic and mechanical aspects of beat maintenance, resulting in comparable performance to younger individuals when tapping with a metronome.

Previous research indicates that during movement performance in older adults, additional brain regions, specifically prefrontal areas, become active [83–85], even in situations where there are no age-related differences in performance outcomes. This suggests increased cognitive control in executing movements in older individuals. Thus, there might be a beginning decline in motor control associated with aging, which people compensate for by employing extra neural and cognitive resources, leading them to achieve performance levels comparable to those of younger individuals when the task is simple, such as metronome tapping in this study. However, in tasks that demand higher-level representations and/or executive control such as bimanual [86–89] and sequential [90] tapping, or having to rapidly extract the beat from a musical sequence such as in this study, these compensatory mechanisms might not be sufficient, leading to age-related differences in performance in these more complex tasks. The global effect of MMSE on consistency discussed in the previous section may also imply that people with NCD do not engage in compensatory mechanisms as efficiently as healthy older adults, or that this compensation is not sufficient to mask differences in performance even on simpler tasks like tapping with a metronome. For future research, it is crucial to use stimuli with varying levels of complexity, as in this study, to discern the factors that yield observable performance differences.

Implications for music-based interventions

The results highlight that motor and cognitive skills may be tightly linked, indicating the potential of rhythm-based interventions to stimulate non-motor domains, such as working memory, executive functions, language, and socio-emotional functioning, presenting a promising avenue for improving the quality of life in individuals with NCDs. The current findings are relevant to how interventions may be tailored to a person's cognitive status. Considering that individuals with lower cognitive functioning may have difficulties in synchronizing movements to auditory stimuli, particularly those that are not intrinsically motivating or rewarding, it is essential to adapt music-based interventions based on cognitive ability and carefully select appropriate stimuli. One may consider using stable and predictable beats, potentially including metronomes or music with high beat clarity when working with older adults, given the age-related decline in beat induction demonstrated here. Indeed, previous studies have used music with beats sonically enhanced or reinforced by a superimposed metronome to facilitate synchronization in a rehabilitative setting [72, 91, 92] The observed reduction in consistency when introducing tempo changes could serve as an argument for adaptive programs, starting with simpler, stable tempi and gradually introducing more complex rhythms to ensure task engagement and build rhythmic skills progressively. While our research and its implications for rhythm-based interventions are focused on simple, unimanual tapping, it is essential to note that music-based interventions requiring finer motor control may specifically engender cognitive benefits [93]. While this study did not compare audio-visual stimuli with purely auditory stimuli, the high levels of performance observed here suggest that visual cues of any kind may enhance synchronization. Finally, non-musical cognitive training could be intertwined with musical exercises, mutually enhancing each other's effectiveness.

Limitations

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

We recognized the importance of good hearing and vision for our experiment, screening out potential participants with impairments or those who did not have the necessary aids with them. However, we did not conduct formal audiometry or visual acuity tests, leaving the possibility that performance variations could be attributed in part to differences in hearing and visual abilities, considering the common prevalence of hearing loss [94] and visual impairment [95, 96] in older adults.

It is worth repeating that we deliberately chose to use audio-visual stimuli to synchronize to, a manipulation deemed necessary to maintain participants' engagement and motivation throughout the task. Nevertheless, this prevented us from assessing the degree to which participants relied on auditory versus visual information. Especially in terms of beat induction and beat maintenance, it is conceivable that the presentation of sensory information through different modalities could impact them in different ways. An interesting path for future investigation is to compare how these processes are influenced when information is presented solely through auditory, solely through visual, or through both modalities.

Concluding remarks

This study highlights two primary findings. The first is an influence of MMSE score on tapping consistency, irrespective of audio stimulus type and of the presence or absence of tempo changes, suggesting an effect of NCD severity on the ability to maintain a steady rhythm. Two possible mechanisms could explain this, which are not mutually exclusive. Firstly, neural reorganizing over the course of the disorder may increasingly engage non-motor areas to sustain performance during a simple motor task, indicating a shift towards more cognitive and effortful processing of rhythm. Secondly, even simple metronome tapping may require some degree of attention and working memory, albeit less than tapping with music. Healthy aging individuals may therefore maintain a consistent level of performance when tapping with a metronome, whereas in more cognitively impaired individuals with a lower MMSE, the impairment of attention and working memory is severe enough to significantly hinder performance, even in tapping with a simple metronome, arguably the simplest form of SMS. However, it is important to acknowledge the importance of tempo changes in half of the trials. While the statistical analysis indicates that the impact of cognitive impairment held for both conditions (with and without tempo changes), it may still be that the primary difficulty in this study might have arisen from the presence of tempo changes in half of the trials, even though the difference in decline of consistency as a function of MMSE across the two levels of tempo stability was not large enough to yield statistical significance. Although we did not observe an interaction between tempo stability and MMSE in this study, the current results do not eliminate the possibility that individuals with NCD might experience specific difficulties in adapting to tempo changes. The involvement of working memory, attention, and cognitive flexibility in error correction could still play a role, warranting further investigation. The second result shows an age-related decline in consistency during SMS but only when tapping with music, whereas consistency remains stable when tapping with a metronome. This observation implies that beat induction, a process especially relevant for perceiving the underlying beat in musical sequences, is affected in healthy aging, potentially indicating a beginning decline of attention and working memory. Beat maintenance, on the other hand, may be relatively spared.

In conclusion, this research emphasizes the importance of sensorimotor impairment as a symptom in NCD. The findings suggest that motor and cognitive skills may be tightly linked, implying that deficits in one domain may potentially impact the other. This interplay underlines the potential for rhythm-based training to inadvertently stimulate non-motor domains, such as working memory, executive functions, language, and socio-emotional functioning, presenting a promising avenue for enhancing the quality of life in individuals living with NCDs. These insights provide a foundation for continued research and therapeutic interventions aimed at enhancing well-being in healthy and pathological aging by targeting the sensorimotor domain. The possibility for therapeutic approaches are vast, ranging from group drumming [97] to remote interventions using mobile devices [98].

AUTHOR CONTRIBUTIONS

Andres von Schnehen (Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Writing – original draft); Lise Hobeika (Conceptualization; Formal analysis; Methodology; Software; Supervision; Writing – review & editing); Marion Houot (Formal analysis; Software; Writing – review & editing); Arnaud Recher (Resources; Software); François Puisieux (Resources; Supervision); Dominique Huvent-Grelle (Resources; Writing – review & editing); Séverine Samson (Conceptualization; Funding acquisition; Supervision; Validation; Writing – review & editing).

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During the preparation of this work the authors used the large language model ChatGPT [99] in order to improve the flow and readability of the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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CONFLICT OF INTEREST

The authors have no conflict of interest to report.

DATA AVAILABILITY

The data supporting the findings and a script to analyze them are openly available at https://osf.io/78k46/?view_only=9e15fa4ac33d49e1aff47bd609c305ab.

SUPPLEMENTARY MATERIAL

The supplementary material is available in the electronic version of this article: https://dx.doi.org/10.3233/JAD-231433.

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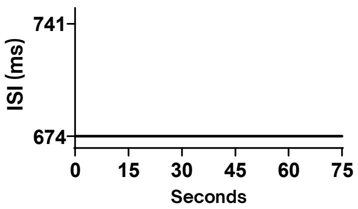
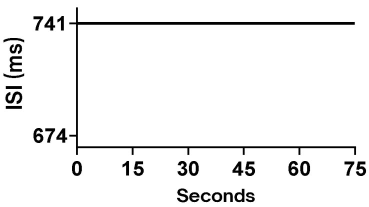
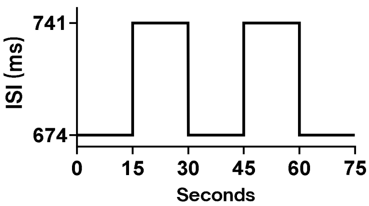
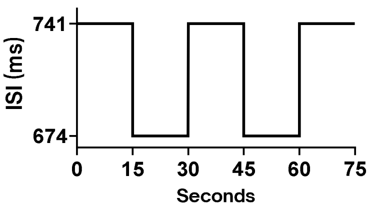
Supplementary Material

Sensorimotor Impairment in Aging and Neurocognitive Disorders: Beat Synchronization and Adaptation to Tempo Changes

Supplementary Table 1. Musician's performance. When recording the videos of the musician tapping synchronously with the auditory sequences, inter-tap interval and coefficient of variation were verified to ensure that the musician tapped with minimal error.

	Inter-tap interval (ms)	Coefficient of variation
	8.90	0.40
	1.01	0.05
	-0.11	0.00
	-0.85	0.02

Supplementary Table 2. Demographic and clinical information of patients who withdrew from the study during the experiment.

	N	Median [first quartile, third quartile] or frequencies (%)	Range
Age	7	88 [84, 94]	81-95
Gender (women)	7	5 (71%)	
Years of education	7	12 [7, 14]	5-14
Musical expertise (out of 28)	7	3 [2, 4]	0-4
Major NCD		6 (100%)	
Minor NCD		0 (0%)	
No NCD		0 (0%)	
MMSE (out of 30)	7	21 [20, 25]	17-29
ADL (out of 6)	7	5.5 [4, 6]	2-6
IADL (out of 4)	7	1 [0, 2]	0-4
GDS (out of 15)	6	4 [3, 7]	2-7
GAI (out of 5)	6	1 [1, 1]	0-4

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

Supplementary Table 3. Model summary and significance tests: consistency

	Wald χ^2	df	p	f^2
Audio	**76.437**	**1**	**<0.001**	**0.036**
Tempo stability	**756.336**	**1**	**<0.001**	**0.209**
Age	1.750	1	0.186	0.011
MMSE	**3.863**	**1**	**0.049**	**0.032**
Audio:Age	**4.283**	**1**	**0.038**	**0.002**
Tempo stability:Age	**8.579**	**1**	**0.003**	**0.010**
Audio:MMSE	0.460	1	0.497	<0.001
Tempo stability:MMSE	1.034	1	0.309	0.004
Sex	0.103	1	0.748	0.002
Years of education	0.531	1	0.466	0.015
Musical expertise	1.095	1	0.295	0.027

Significant results are highlighted in **bold**.
MMSE, Mini-Mental State Examination

Supplementary Table 4. Model summary and significance tests: asynchrony

	Wald χ^2	df	p	f^2
Audio	**248.075**	**1**	**<0.001**	**1.381**
Sex	0.328	1	0.567	1.032
Years of education	1.198	1	0.274	1.035
Musical expertise	2.455	1	0.117	1.045

Significant results are highlighted in **bold**.

Supplementary Table 5. Model summary and significance tests: consistency (complete model)

	Wald χ^2	df	p	f^2
Sex	0.121	1	0.728	0.002
Years of education	0.524	1	0.469	0.014
Musical expertise	1.127	1	0.289	0.026
Audio	**80.249**	**1**	**0.000**	**0.024**
Tempo	0.011	1	0.916	<0.001
Tempo stability	**810.620**	**1**	**0.000**	**0.213**
Segment	**11.364**	**1**	**0.010**	**0.004**
Age	1.717	1	0.190	0.011
MMSE	**3.843**	**1**	**0.050**	**0.033**
Audio:Tempo	1.024	1	0.311	<0.001
Audio:Tempo stability	**5.473**	**1**	**0.019**	**<0.001**
Audio:Segment	**18.214**	**1**	**0.000**	**0.007**
Tempo:Tempo stability	0.066	1	0.798	<0.001
Tempo:Segment	5.803	1	0.122	0.002
Tempo stability:Segment	**11.012**	**1**	**0.012**	**0.004**
Audio:Age	**4.500**	**1**	**0.034**	**0.002**
Tempo:Age	0.330	1	0.565	<0.001
Tempo stability:Age	**9.880**	**1**	**0.002**	**<0.001**
Audio:MMSE	0.579	1	0.447	<0.001
Tempo:MMSE	0.035	1	0.851	<0.001
Tempo stability:MMSE	0.815	1	0.367	<0.001
Audio:Tempo:Tempo stability	3.376	1	0.066	0.001
Audio:Tempo:Segment	1.966	1	0.579	<0.001
Audio:Tempo stability:Segment	5.127	1	0.163	0.002
Tempo:Tempo stability:Segment	3.463	1	0.326	<0.001
Audio:Tempo:Age	1.957	1	0.162	<0.001
Audio:Tempo stability:Age	**5.577**	**1**	**0.018**	**0.001**
Tempo:Tempo stability:Age	0.076	1	0.783	<0.001
Audio:Tempo:MMSE	**7.301**	**1**	**0.007**	**0.003**
Audio:Tempo stability:MMSE	0.070	1	0.791	<0.001
Tempo:Tempo stability:MMSE	0.622	1	0.430	<0.001
Audio:Tempo:Tempo stability:Segment	1.948	1	0.583	0.001
Audio:Tempo:Tempo stability:Age	1.524	1	0.217	0.002
Audio:Tempo:Tempo stability:MMSE	2.274	1	0.132	<0.001

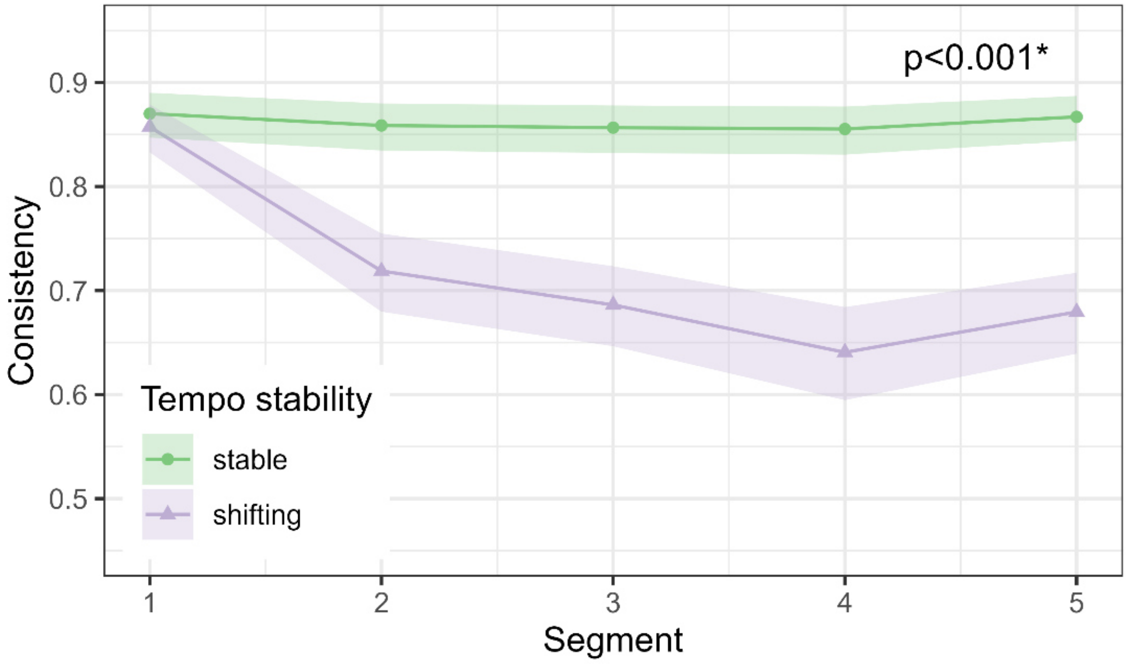
The complete model was run to control for any possible confounding effects. The fact that the effects of interest were significant in both models suggests that they are not explained by factors such as tempo or segment that are not included in the final model.
Significant results are highlighted in **bold**.
MMSE, Mini-Mental State Examination

Supplementary Table 6. Model summary and significance tests: asynchrony (complete model)

	Wald χ^2	df	p	f^2
Sex	1.209	1	0.271	0.003
Years of education	0.000	1	0.998	<0.001
Musical expertise	1.206	1	0.272	0.006
Audio	**942.673**	**1**	**0.000**	**0.228**
Tempo	**405.880**	**1**	**0.000**	**0.150**
Tempo stability	**14.052**	**1**	**0.000**	**0.023**
Segment	**257.757**	**1**	**0.000**	**0.063**
Age	0.519	1	0.471	0.001
MMSE	3.414	1	0.065	0.010
Audio:Tempo	**164.965**	**1**	**0.000**	**0.080**
Audio:Tempo stability	0.001	1	0.981	0.024
Audio:Segment	**53.955**	**1**	**0.000**	**0.041**
Tempo:Tempo stability	**627.589**	**1**	**0.000**	**0.355**
Tempo:Segment	**502.312**	**1**	**0.000**	**0.343**
Tempo stability:Segment	**138.652**	**1**	**0.000**	**0.115**
Audio:Age	3.280	1	0.070	<0.001
Tempo:Age	**5.261**	**1**	**0.022**	**<0.001**
Tempo stability:Age	**4.838**	**1**	**0.028**	**0.001**
Audio:MMSE	**6.248**	**1**	**0.012**	**0.002**
Tempo:MMSE	0.532	1	0.466	<0.001
Tempo stability:MMSE	3.512	1	0.061	<0.001
Audio:Tempo:Tempo stability	**47.736**	**1**	**0.000**	**0.052**
Audio:Tempo:Segment	**84.868**	**1**	**0.000**	**0.093**
Audio:Tempo stability:Segment	**124.403**	**1**	**0.000**	**0.112**
Tempo:Tempo stability:Segment	**502.271**	**1**	**0.000**	**0.624**
Audio:Tempo:Age	**4.400**	**1**	**0.036**	**0.001**
Audio:Tempo stability:Age	2.264	1	0.132	0.001
Tempo:Tempo stability:Age	2.816	1	0.093	<0.001
Audio:Tempo:MMSE	1.138	1	0.286	<0.001
Audio:Tempo stability:MMSE	1.363	1	0.243	<0.001
Tempo:Tempo stability:MMSE	0.183	1	0.668	<0.001
Audio:Tempo:Tempo stability:Segment	**154.493**	**1**	**0.000**	**0.015**
Audio:Tempo:Tempo stability:Age	2.864	1	0.091	0.001
Audio:Tempo:Tempo stability:MMSE	2.276	1	0.131	<0.001

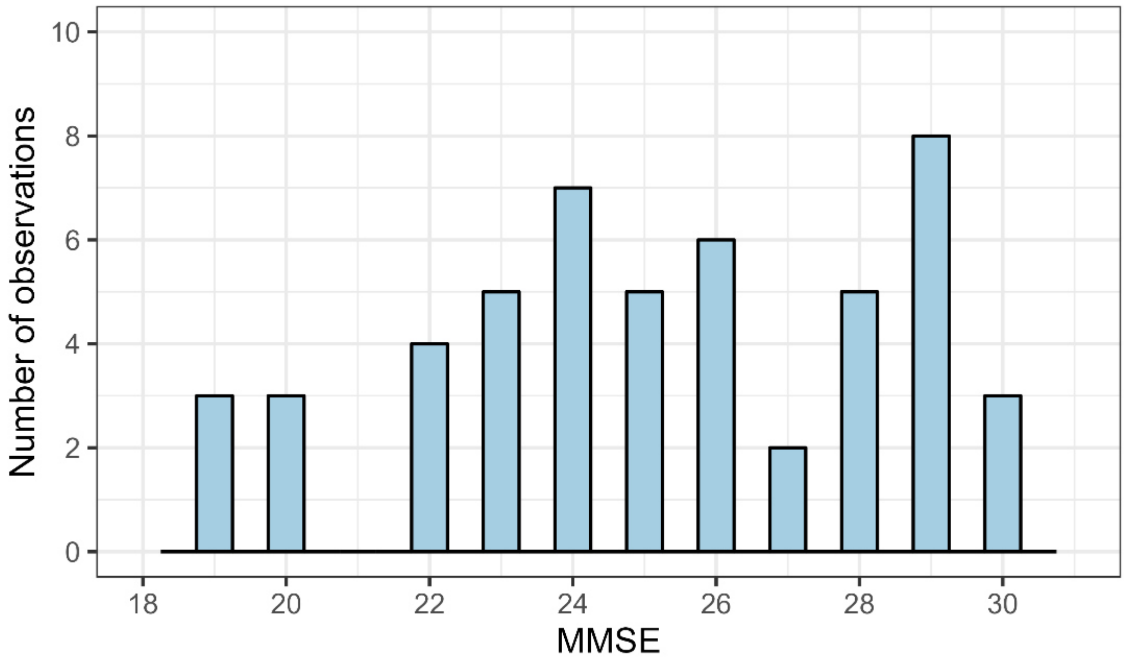
As for consistency, the complete model was run to control for any possible confounding effects. The fact that the effects of interest were significant in both models suggests that they are not explained by confounding factors that are not included in the final model.
Significant results are highlighted in **bold**.
MMSE, Mini-Mental State Examination

Supplementary Figure 1. Effects of segment and stability on consistency



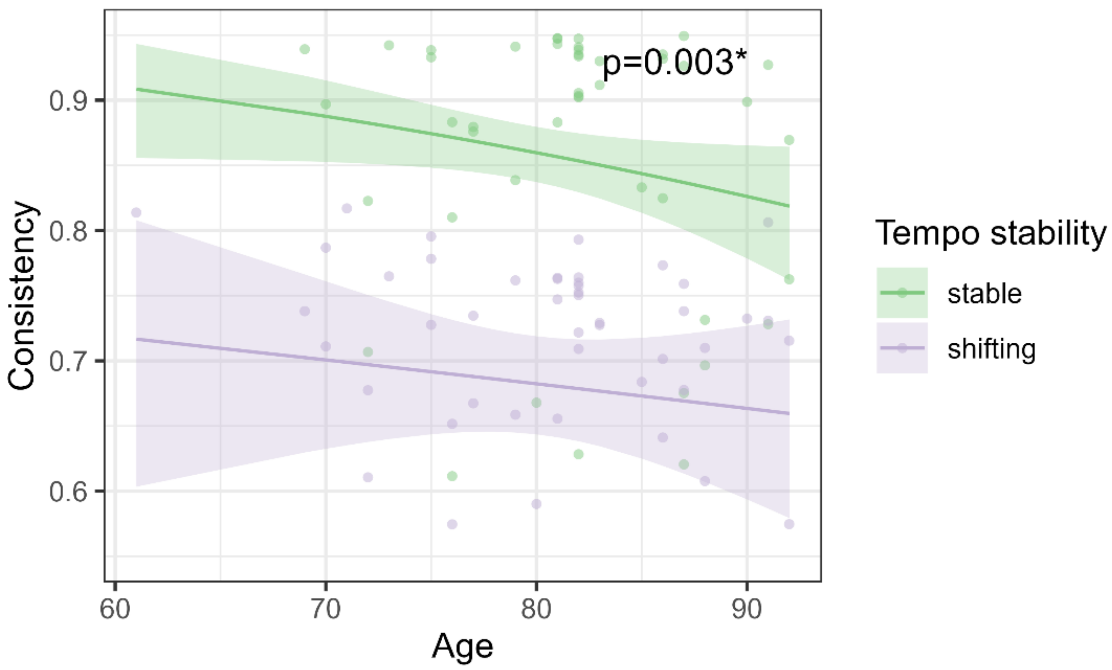
Consistency was calculated for the different segments in the presence and absence of tempo changes, highlighting the drop in performance as a result of changes in tempo.

Supplementary Figure 2. Distribution of MMSE



MMSE, Mini-Mental State Examination

Supplementary Figure 3. Effects of age and tempo stability and consistency



Chapter 5

The role of age and musical expertise in sensorimotor synchronization with music and metronomes

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Abstract

Sensorimotor synchronization (SMS) is the process of aligning motor output with rhythmic sensory stimuli, such as music or a metronome. The effects of aging and musical expertise in SMS remain under-explored, especially when it comes to synchronization with music. This study aimed to close this gap by having young and older healthy adults engage in an SMS task with musical and metronomic sequences, half of which contained sudden tempo changes. Musical expertise was quantified using the Goldsmiths Musical Sophistication Index (Gold-MSI). Results indicated that age did not significantly predict synchronization consistency, which was generally high for participants in both age groups. However, Gold-MSI scores were associated with SMS performance. In terms of asynchrony, participants generally tapped ahead of the beat with a metronome, irrespective of age or musical expertise. While synchronizing with music, younger participants and those with less musical experience exhibited more negative asynchrony. These findings suggest that age may only impact SMS performance in the later decades of life. Moreover, the study challenges the belief that negative mean asynchrony occurs solely with metronomic sequences and not with music.

Introduction

Sensorimotor synchronization (SMS) refers to the temporal coordination of a motor action with rhythmic sensory input (Repp, 2005). SMS is crucial to a wide range of abilities, including cognitive and speech functions, making it an important area of study. The ability to attend to temporal regularities in the environment is a prerequisite for event prediction, which underlies many cognitive and social operations. This ability is necessary in various interpersonal contexts, from joint music making (Sebanz et al., 2006) to spoken language, which contains notable temporal regularities (Poeppel & Assaneo, 2020). Musical activities are thought to train cognition in aging (Marie et al., 2023; Worschech et al., 2021), but the impact of age on SMS and the potential for training to mitigate age-related effects remain under-researched. In particular, there is a lack of studies investigating SMS to music, particularly among older adults (von Schnehen et al., 2022).

Existing studies generally did not find significant effects of age on synchronization performance, at least not when using simple sequences at a comfortable tempo (Drewing et al., 2006; Duchek et al., 1994; Krampe et al., 2005; McAuley et al., 2006; Turgeon et al., 2011; Vanneste et al., 2001). However, age-related effects have been observed under specific conditions: when the tempo was very slow (McAuley et al., 2006) or very fast (Carment et al., 2018); when rhythms were more complex (Drewing et al., 2006, p. 2); or when individuals simultaneously engaged in a cognitively demanding task (Krampe et al., 2010).

In a recent study (von Schnehen et al., 2024), we investigated SMS in patients at a geriatric hospital, most of whom had problems related to memory or falls. We used metronomic and musical sequences with and without tempo changes, measuring SMS in terms of consistency (stability of the relative phase between taps and beats) and asynchrony (the degree to which participants tap before or after the beat) (Sowiński & Dalla Bella, 2013). Our findings revealed an age effect specific to music: While synchronization consistency remained high across different ages when synchronizing with a metronome, an age-related decline in performance was observed with music. While that study included participants aged from their 60s up to their 90s and spanning a spectrum from cognitively healthy individuals to those with major neurocognitive disorder, it lacked a younger comparison group and a cohort of healthy older adults. To better understand the effects of healthy aging, the current study includes these groups.

In addition, the current study aimed to investigate the effect of musical experience on synchronization consistency and asynchrony, and how it would interact with age. While a few studies have explored this topic, their findings have been inconclusive. Generally, musicians demonstrate higher tapping consistency (Drake et al., 2000; Merten et al., 2019; Snyder et al., 2006; Thompson et al., 2015; Whitton & Jiang, 2023). Regarding asynchrony, some research suggests lower negative asynchrony in musicians (Merten et al., 2019; Thompson et al., 2015), while other studies indicate no differences between musicians and non-musicians (Slater et al., 2013; Snyder et al., 2006). Most of these studies have treated musicianship as a binary variable, comparing musicians to non-musicians. In contrast, our study uses the Goldsmiths Musical Sophistication Index (Gold-MSI) (Müllensiefen et al., 2014), as a continuous measure of musical sophistication that encompasses a broader range of musical experiences beyond formal training.

The main objective of the study was thus to examine whether age and/or musical expertise may influence auditory-motor integration. To achieve this, we used a hand-tapping task in which a group of young and a group of older healthy participants synchronized their movements to musical and metronomic sequences, half of which contained sudden tempo changes. The use of tempo changes enabled us to test error correction in SMS. Error correction is an ever-present process that prevents gradual misalignment (Hary & Moore, 1987; Vorberg & Wing, 1996). We aimed to determine whether this error correction process might be compromised in older individuals.

We predicted that participants would exhibit higher tapping consistency and more negative asynchrony when tapping with a metronome compared to music, like in previous studies (Aschersleben, 2002; Dalla Bella et al., 2017; Ghilain et al., 2020; Sowiński & Dalla Bella, 2013). Additionally, we expected lower consistency when the tempo was shifting compared to when it was stable. For older participants, we expected lower consistency when tapping with music, as demonstrated in a previous study (von Schnehen et al., *submitted*). Next, we expected an interaction between age and tempo stability, such that the reduction in consistency following tempo changes would be exacerbated in older people. Finally, we hypothesized that higher Gold-MSI score would be related to higher consistency and less negative asynchrony (Aschersleben, 2002; Baer et al., 2015; Chen et al., 2008; Ireland et al., 2018; Merten et al., 2019; Repp, 2004, 2010).

Methods

Participants

We recruited 42 younger (aged 18 to 35 years) and 47 healthy older participants (aged 65 years and above), all of whom were right-handed. Younger participants were recruited from the University of Lille campus, whereas older participants were recruited through pensioners' associations. Exclusion criteria included neurological, psychiatric, or motor disorders, uncorrected vision and auditory problems, and left-handedness. Additionally, in the group of older adults, we administered the mini-mental state examination to screen for cognitive impairment and to exclude participants who scored below the cut-off score of 25 for intact cognitive function (Folstein et al., 1983). This screening led to the exclusion of one participant. The data of the remaining 88 participants were subjected to analysis. This study was approved by the local Ethics Committee (*Comité d'Éthique de Recherche* 2022-579-103, University of Lille), and all patients provided written informed consent in accordance with the Declaration of Helsinki.

Apparatus, stimuli, and procedure

Participants were seated across from a screen (60 cm height x 34 cm length) and a pair of loudspeakers at a distance of one meter. The setup was designed for the presentation of auditory sequences, along with a video recording of a musician tapping to the beat. The stimuli were presented, and responses collected using a custom program written in MAX/MSP (https://cycling74.com). The stimuli lasted 75 seconds, preceded by a 4-beat intro to establish the initial tempo. They consisted of either a simple metronome or a MIDI rendition (without lyrics) of a French folk song. Inter-stimulus intervals were set at 674 ms (fast stable tempo), 741 ms (slow stable tempo), or shifted between the two (shifting conditions). Participants first completed the Edinburgh Handedness Questionnaire (Oldfield, 1971) to confirm their right-handedness, followed by the Gold-MSI to assess their musical sophistication across various domains. The older group also completed the MMSE. Next, participants engaged in the synchronization task, during which they were asked to synchronize by tapping every beat on the tablet with the probe. After a training trial with a different song, eight experimental trials were carried out in a randomized order, counterbalanced across participants.

Data analysis

Due to tempo changes occurring every 15 seconds in half of the trials, trials were subdivided into 15-second segments and consistency and asynchrony were computed per segment using circular statistics (Fisher, 1995) with the CircStat toolbox (Berens, 2009) in MATLAB (The MathWorks Inc, 2022), starting from the second segment (after 15 seconds).

Statistical analyses were conducted in R (R Core Team, 2024) using RStudio (RStudio Team, 2024). First of all, we tested for significant differences between the younger and older group in terms of gender using Fisher's exact test, and in terms of education and Gold-MSI score using the Wilcoxon rank-sum test. Next, we removed all observations in which asynchrony was below -135° or above 135° relative to the beat, indicating tapping in antiphase. This resulted in the removal of 6.8% of the observations. Two separate mixed-effects models were then applied to analyze synchronization consistency and asynchrony, respectively.

For the analysis of consistency, we employed a generalized linear mixed model with a beta distribution and a logit link. Fixed effects included audio type (music/metronome), tempo stability (stable/shifting), age group (younger/older), Gold-MSI score, and interactions between audio type and age group, tempo stability and age group, and audio type and Gold-MSI score. Participant was included as a random effect.

In the asynchrony analysis, segments with insufficient taps (i.e., where the number of taps relative to the number of beats was at least two standard deviations below the mean) and those in which performance was at chance level, according to the Rayleigh test for circular uniformity (Wilkie, 1983), were removed. This led to an additional removal of 2.4% of the observations.

Asynchrony was transformed by taking the cubic root of its absolute value and multiplying it by its original sign to meet the assumption of normality of residuals. We then conducted a linear mixed-effects model analysis using the same fixed and random effects as the consistency model, except for tempo stability and its interactions, for which no hypotheses were proposed.

In both analyses, gender and years of education were included as control variables. As they showed no significant effects and did not alter the significant results, they were subsequently removed. For the consistency analysis, Type II Wald chi-square tests were used to test the effects of the two mixed-models analysis, while F tests were calculated for the asynchrony analysis. Effect sizes were calculated as f^2.

Results

Table 1 provides demographic information for younger and older participants. The two groups did not significantly differ in terms of gender (p = .818), years of education (W = 1110, p = .223), or Gold-MSI score (W = 1027, p = .613).

Table 1

Demographic information of the two groups of participants

	Younger (N = 42)		Older (N = 46)		p
	Median [first quartile, third quartile] or frequencies (%)	Range	Median [first quartile, third quartile] or frequencies (%)	Range	
Age	23 [21, 25]	18-32	70 [68, 73]	64-81	**< .001**
Gender	30 women (71%)		31 women (67%)		.818
Years of education	15 [15, 17]	12-20	15 [12, 17]	9-20	.223
Gold-MSI score	76 [68.25, 88.75]	48-109	77 [66.25, 83.75]	52-107	.613
MMSE	-		30 [29, 30]	27-30	

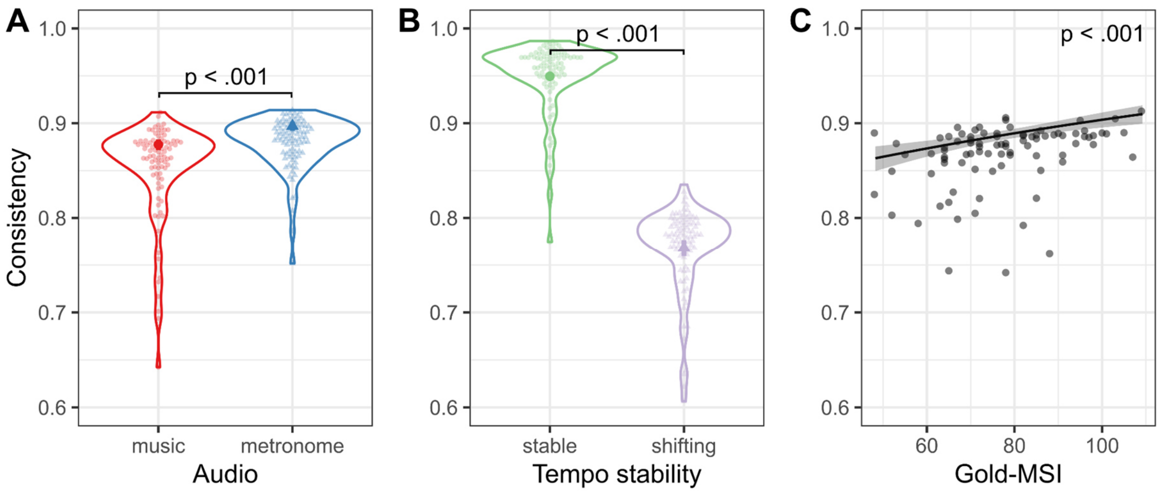
Note. Group differences were assessed using the Wilcoxon rank-sum test for numeric variables and Fisher's exact test for gender. Gold-MSI: Goldsmiths Musical Sophistication Index; MMSE: mini-mental state examination

For the analysis of synchronization consistency, a significant effect of audio type was observed (*Wald* χ^2 = 93.92, p < .001, f^2 = 0.03). Consistency was higher when participants tapped with the metronome compared to the musical stimulus (Figure 1A). As expected, there was a significant effect of tempo stability (*Wald* χ^2 = 5,678.27, p < .001, f^2 = 1.39). Consistency was higher when the tempo remained stable than when it contained tempo changes (Figure 1B). Finally, an effect of Gold-MSI score was found, (*Wald* χ^2 = 19.79, p < .001, f^2 = 0.03). Higher scores on the

Gold-MSI were associated with greater tapping consistency. (Figure 1C). The main effect of age group was not significant.

Figure 1

Synchronization consistency in relation to audio type (A), tempo stability (B), and score on the Gold-MSI (C)

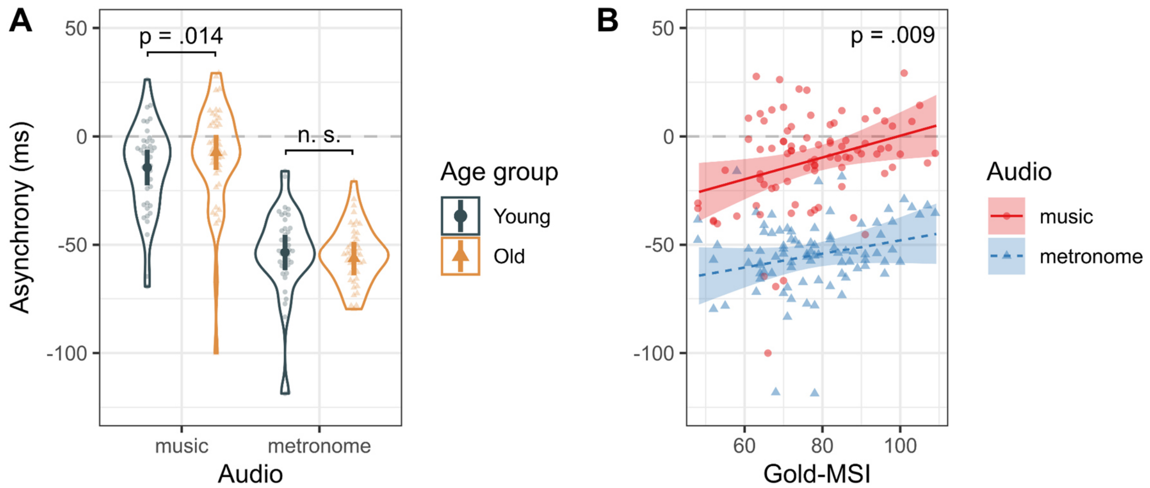


Gold-MSI: Goldsmiths Musical Sophistication Inventory

In the analysis with asynchrony as a dependent variable, significant effects were found for audio type (F = 337.42, p < .001, f^2 = 0.05) and Gold-MSI score (F = 16.34, p < .001, f^2 < 0.01). Moreover, an interaction between audio type and age group was observed (F = 6.40, p = .012, f^2 < 0.01). Post hoc tests, adjusted for multiple testing using the Benjamini-Hochberg method, revealed that when tapping with metronome, participants' taps anticipated the beats by several tens of milliseconds, with no significant difference between younger and older participants. However, when tapping with music, older participant's taps were closer to the beats, whereas younger participants' taps still anticipated the beats, though not as strongly as with the metronome (Figure 2A). Finally, there was an interaction between audio type and Gold-MSI score ($F = 6.93$, $p = .009$, $f^2 < 0.01$). Post hoc tests were used to determine if the slopes of the two levels of the variable audio type differed significantly from zero. Only the slope for music was positive and significantly different from zero ($p < .001$), whereas the slope for the metronome was not significantly different from zero ($p = .055$). This suggests that when tapping with a metronome, participants' taps anticipated the beat by several tens of milliseconds, regardless of musical sophistication. However, when tapping with music, only the taps of people with less musical experience tended to occur before the beat, whereas individuals with higher Gold-MSI scores tended to tap on the beat (Figure 2B). The main effect of age group was not significant.

Figure 2

Synchronization asynchrony as a function of audio type and age group (A), and of audio type and Gold-MSI score (B)



Gold-MSI: Goldsmiths Musical Sophistication Inventory

Discussion

The current study investigated how participant characteristics (age and musical expertise) influence SMS performance, quantified as consistency and asynchrony. First of all, we replicated four effects that we observed in previous studies: higher consistency when tapping with a metronome than with music (Dalla Bella et al., 2017; Ghilain et al., 2020); lower consistency in trials with a shifting tempo (von Schnehen et al., 2024); higher consistency in people with musical experience (Baer et al., 2015; Chen et al., 2008; Drake et al., 2000; Ireland et al., 2018; Merten et al., 2019; Repp, 2010; Slater et al., 2013; Snyder et al., 2006);

and lower asynchrony when tapping with music compared to a metronome (Aschersleben, 2002; Sowiński & Dalla Bella, 2013).

The observation of higher synchronization consistency with higher Gold-MSI scores is not surprising, given that precise rhythm production is a key component of musical performance, and musical training is thought to improve timing accuracy and the ability to extract the beat from a musical sequence (Grahn & Rowe, 2009; Kincaid et al., 2002). However, the possibility of pre-existing differences must always be considered in cross-sectional research: People with naturally better beat-keeping skills might be more drawn to pursuing music (Orsmond & Miller, 1999)

Next, we aimed to determine whether the interaction between age and audio type observed in our previous study (von Schnehen et al., 2024) would generalize to a sample of cognitively healthy young and older adults. In the previous study, synchronization consistency declined with age when participants synchronized with music, but not with a metronome. However, that study only included older adults, focusing on development in the later decades of life. In contrast, the current study compared younger participants, primarily in their twenties, with older participants with a median age of 70. We did not observe an impact of age on consistency, either directly or through an interaction with audio type or tempo stability. Integrating the current results with our previous study suggests that age-related declines in SMS may only begin in the later decades of life. This interpretation aligns with a study by McAuley et al. (2006), which reported age-related declines in synchronization performance specifically for participants aged 75 and above. Alternatively, it is possible that the sample in our previous study was more cognitively vulnerable, making them more susceptible to age-related sensorimotor impairment.

Additionally, we predicted an interaction between age and tempo stability, expecting that the reduction in consistency during trials with a shifting tempo would be more pronounced in the older group, but this effect was not significant. However, the possibility that age affects adaptation to tempo changes cannot entirely be ruled out. The task and its analysis, which examined consistency in 15-second segments, may not have been precise enough, since people typically adapt to a new tempo within just a few taps (Repp & Keller, 2004; Thaut et al., 1998). Furthermore, the bimodal nature of the task (audio and video) might have made the task easier, mitigating the difficulty introduced by the tempo changes.

Finally, tapping asynchrony was influenced by interactions between task characteristics and participant characteristics in two notable ways: Participants' taps tended to occur several tens of milliseconds before the beat when tapping with a metronome, regardless of age group or musical experience. However, when tapping with music, asynchrony varied based on both age group and musical expertise. Specifically, older adults and individuals with higher Gold-MSI scores tended to tap close to the beat, whereas younger participants and those with less musical experience tended to tap slightly before the beat, albeit not as much as people tended to do with a metronome. This negative mean asynchrony - the tendency for participants' taps to precede the corresponding beats - is both ubiquitous and puzzling in SMS research (Repp & Su, 2013). It is believed to reflect the subjective impression of tapping in synchrony with the beat (Aschersleben, 2002; Repp, 2005). It has been shown to be reduced when inter-stimulus intervals are reduced (Repp, 2003) and it has been suggested that this asynchrony is an error in time estimation occurring only in empty intervals, where the duration is underestimated, causing the tap to occur too soon. Consequently, it has been proposed that the negative mean asynchrony is absent when people tap with music, where inter-stimulus intervals are subdivided by many musical events (Wohlschläger & Koch, 2000). However, the current results, while demonstrating lower asynchrony with music than with a metronome, challenge the assumption that the negative mean asynchrony would be entirely absent with music. Instead, they indicate that this asynchrony is influenced by factors such as the listener's age or musical experience. A reduction in asynchrony with a metronome has been demonstrated in musicians before (Aschersleben, 2002; Repp, 2004, 2010), but to our knowledge, this has never been shown with music. While our use of the Gold-MSI represents an improvement compared to just using two groups of musicians vs. non-musicians, it remains limited. A future study could look more precisely at types of musical experiences, since it has been demonstrated, for example, that percussionists synchronize with lower asynchronies than other types of musicians (Krause et al., 2010) Regarding the lower asynchrony in older individuals when tapping with music, this effect is more difficult to interpret: Perhaps older people have more lifelong experience in musical or other activities that require synchronization, contributing to more accurate timing.

In sum, our study contributes to the literature on SMS, demonstrating that the previously observed effect of aging on synchronization consistency may only apply in the later decades of life or among cognitively vulnerable groups, such as those with neurocognitive disorders. In addition, we demonstrate that negative asynchrony can occur even when individuals synchronize with music, but this phenomenon is influenced by both age and musical experience.

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Chapter 6

Cognitive processes underlying synchronization to music in older adults with and without neurocognitive disorder

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Cognitive processes underlying synchronisation to music in older adults with and without neurocognitive disorder

Running head: Cognition and music synchronisation in NCD

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Impact statement: We certify that our research provides novel insights into the dynamics of sensorimotor synchronisation to music in elderly adults with and without neurocognitive disorders. Using large samples in our two analyses (N = 177 and N = 97) and a task specifically designed for this population, we identify specific cognitive functions, namely short-term memory and inhibitory control, that play a role in beat extraction from music.

Key points:

- Mini-mental state examination scores affected consistency in tapping to a metronome, while age negatively affected consistency in tapping to music, suggesting different cognitive processes for each task.
- Short-term memory and inhibitory control predicted successful synchronisation to music but not to a metronome.
- The results suggest that metronome tapping is more automatic while music tapping requires more complex cognitive processing.

Why does this paper matter? Advancing the understanding of the links between rhythmic and cognitive functions is crucial to developing music-based interventions in older adults with neurodegenerative disorders, which may improve their quality of life and ideally stimulate their cognitive functioning.

1. ABSTRACT

INTRODUCTION: Synchronisation with regular auditory input is a fundamental aspect of human behaviour, yet the cognitive processes underlying this ability remain underexplored, particularly in older adults with neurodegenerative disorders.

METHODS: 177 older adults performed a synchronisation task with music and a metronome, and their synchronisation consistency was evaluated as a function of age and mini-mental state examination (MMSE) scores. In a subset of 97 participants, short-term memory, working memory, and inhibition were also evaluated.

RESULTS: MMSE scores were associated with consistency only for metronome tapping, whereas age negatively affected synchronisation consistency when tapping with music specifically. Additionally, short-term memory and inhibitory control predicted successful synchronisation to music.

DISCUSSION: We observe a dissociation between metronome tapping and music tapping, where the former was impacted by MMSE and the latter by age. Likely, different processes underlie these two tasks, with metronome tapping being relatively automatic and tapping with music involving a more cognitively demanding beat induction process. The finding that short-term memory and inhibition influence tapping with music but not with a metronome, support this interpretation. The observed connection between cognitive abilities and rhythmic skills suggests potential for stimulating cognition through music-based interventions incorporating rhythmic synchronisation, particularly in older adults with varying degrees of neurocognitive disorders. These findings highlight the potential of tailored interventions to harness the therapeutic benefits of music in neurodegenerative disease.

Keywords: aging, music, auditory perception, rhythm, dementia

2. INTRODUCTION

In recent years, there has been an increased interest in rhythmic abilities and the capacity for sensorimotor synchronisation in older adults and individuals with neurocognitive disorder (NCD), commonly referred to as dementia[1]. Strong connections exist between rhythmic abilities and cognitive functions. For instance, research indicates that beat perception and rhythm synchronisation performance are linked to cognitive flexibility, inhibition[2], and working memory[3]. Nevertheless, these associations have not yet been established in the context of ageing and NCD. Music-based interventions are increasingly recommended to enhance the quality of life of individuals with NCDs[4] and also as a preventive strategy for healthy older adults[5]. While the efficacy of these interventions remains unclear, it can be hypothesised that interventions fostering rhythmic synchronisation may be particularly effective by engaging brain networks associated with various functions, notably those involved in cognition and emotion. Research on beat synchronisation and its correlates with cognitive factors may help identify specific exercises that are particularly useful for cognitive stimulation in rehabilitative settings.

Beat perception is composed of two processes: beat induction (finding or extracting a regular pulse) and beat maintenance (mechanical, implicit anticipation of each beat)[6–9]. It has been posited that both processes exist simultaneously during auditory synchronisation, with beat induction being more prominent when beat salience is low (i.e., when the beat is difficult to extract), and beat maintenance prevailing when beat salience is high (i.e., when the beat is easily extracted)[7]. While a single stimulus may vary in beat salience, with moments of higher or lower beat salience prompting the use of beat induction or beat maintenance processes, a simplified assumption implies that synchronising to music (particularly if it contains a certain degree of syncopation) would rely more on beat induction, whereas synchronising to a metronome would predominantly involve beat maintenance. Synchronising with music requires internally generating a beat based on periodicities at several embedded time scales[2], while with a metronome, the beat is arguably contained in the physical signal itself. It has been suggested that cognitive processes such as working memory and attention are involved in extracting a beat from music[10], and this may be true particularly for beat induction. In contrast, beat maintenance, prevalent under conditions of high predictability, is an automatic process with minimal attentional demand. Nevertheless, uncertainty remains regarding the exact cognitive processes underlying beat induction and beat maintenance in individuals with NCD, which this study aimed to address.

In two recent studies[11,12], we identified that NCD severity negatively impacted tapping performance globally, and that tapping with music was specifically affected by age-related decline during the latest decades of life. These outcomes may be attributed to age-related[13,14] or NCD-related[15,16] declines in short-term memory, working memory, and/or inhibition, potentially hampering beat induction while preserving beat maintenance. However, this interpretation remains speculative since the only measure of cognitive function in those studies was the mini-mental state examination (MMSE)[17], a brief evaluation of several dimensions of cognitive function. The first aim of the current study was to extend our prior findings of a negative effect of age and MMSE on synchronisation consistency[12] to a larger sample. Second and more importantly, the current study aimed to explore in more detail the cognitive mechanisms underlying rhythmic synchronisation by using specific cognitive tests and examining the relationships between participants' performance on these tests and their rhythmic synchronisation ability. For this purpose, we used the Digit Span forward and backward tests[18] to assess short-term and working memory, respectively, and the Stroop test[19] as a measure of response inhibition, along with the MMSE. We used two types of audio stimuli (a French folk song and a metronome, identical in length and tempo) and two types of social contexts (live and video). Our task was designed as tapping not just with an auditory sequence but with another person as well, and this person was either really present with them or projected onto a life-sized screen. The manipulation of this social context was discussed in a previous article[20] and is not the focus of the current paper. We hypothesised that individuals scoring lower on the Digit Span forward and backward, and Stroop test, would exhibit inferior tapping consistency, and more negative asynchrony (taps anticipating the beat) when synchronising with music than individuals who perform better on these tests. In contrast, tapping performance might be less dependent or unrelated to performance on these tests when synchronising with a metronome.

3. METHODS

3.1. Participants

During a scheduled consultation related to memory problems or falls, 193 patients were recruited at Lille University Hospital, France. Four participants were excluded as they were not able to complete the synchronisation task. Twelve more patients' data were lost due to technical problems, resulting in a total of 177 participants. All participants were right-handed and native French speakers. This study was approved by the local Ethics Committee (Comité de Protection des Personnes; CPP 18/012) and by the Commission Nationale de l'Informatique et des Libertés (CNIL) and registered at clinicaltrials.gov (NCT04146688). Patients granted written informed consent following the Declaration of Helsinki.

3.2. Apparatus, stimuli, and procedure

The experimental device consisted of two chairs facing each other, each equipped with a tablet with a force sensor on it, allowing participants and the musician to perform the tapping tasks. First, participants' spontaneous motor tempo was assessed by instructing them to tap as regularly as possible at a comfortable tempo for 30 taps. Participants next engaged in the synchronisation task by tapping every beat of the musical and metronomic sequences. Stimuli consisted of 60-second auditory sequences with an inter-stimulus interval of 800 ms that were either a French folk song (music condition) or a sequence of regular beats (metronome condition). For a more detailed description of the experimental apparatus, the stimuli, and the experimental procedure, refer to[20].

Independent of their participation in the current tapping study, patients underwent a geriatric assessment, which included the MMSE for all participants (Model 1), and, for a subset of the patients (Model 2), the Digit Span and Stroop tests. The Digit Span scores (forward and backward) represent the maximum number of digits that participants successfully repeated back in the same or reverse order. Stroop interference is calculated as the time spent on the incongruent version of the task (naming the ink in which a colour word is written, such as the word 'BLUE' written in green ink, while inhibiting the tendency to read out the word itself) subtracted by the time taken to complete a preceding baseline task where participants named the ink of neutral words not related to colours.

3.3. Data analysis

For the analysis of spontaneous motor tempo, the first eight and last two taps were excluded. Mean inter-tap interval and its coefficient of variation were then calculated for the remaining taps.

For the synchronisation task, consistency and asynchrony were computed as a measure of synchronisation performance using circular statistics[21,22] with the CircStat toolbox[23] in MATLAB, version 9.12.0 (The MathWorks Inc., 2022). The Rayleigh test for circular uniformity[24,25] was used to test the null hypothesis that taps are randomly distributed, which could be rejected for all trials, indicating sufficiently high performance. The musician's tapping was also analysed, indicating good performance and minimal error across conditions (all consistency values between .94 and .99).

Statistical analyses were performed in R, version 4.3.1 (R Core Team, 2024), using RStudio, version 2024.4.2.764 (RStudio Team, 2024). Synchronisation consistency and asynchrony were analysed by conducting linear mixed-effect model analyses. Cook's distances were calculated and did not suggest any potential outliers[26]. Consistency was logit-transformed to reduce data skewness[27]. A first analysis of all participants was conducted, including age and MMSE as variables of interest (Model 1; N = 177). A second analysis was then conducted including only participants with complete data on all cognitive tests (Model 2; N = 97). Both analyses included the fixed effects audio (music/metronome), social context (live/video), age, and the interaction between audio and age. Gender, musical expertise, and years of education were added as fixed effects to control for their effects. Participant was added as a random effect. Model 1 additionally included MMSE and the interaction between audio and MMSE. In Model 2, scores on the Digit Span forward, Digit Span backward, Stroop interference, and the interactions between age and each of these cognitive variables were included.

4. RESULTS

Table 1 provides demographic and clinical data of the participants included in the two models. Among the 78 participants with major NCD included in Model 1, 20 were diagnosed with Alzheimer's disease, nine with vascular NCD, 36 with NCD of mixed aetiology, and three with NCD of a different origin. Of the 55 participants with major NCD included in Model 2, 17 were diagnosed with Alzheimer's disease, 8 with vascular NCD, 27 with mixed NCD, and 3 with NCD of a different origin. Participants' mean spontaneous motor tempo was 744 ms (SD = 263 ms), a result similar to what has been found in other studies in a comparable age group[28,29].

Table 1

Demographic and clinical information of patients

	Model 1 (N = 177)		Model 2 (N = 97)	
	Median [first quartile, third quartile] or frequencies (%)	Range	Median [first quartile, third quartile] or frequencies (%)	Range
Age	81 [76, 86]	60-97	82 [77, 86]	63-97
Gender	135 women (76%)		70 women (72%)	
Years of education	8 [6, 10]	4-21	9 [8, 12]	6-23
Musical expertise (out of 28)	3 [2,6]	0-16	3 [2,6]	0-16
Diagnosis				
Major NCD	78 (44%)		55 (57%)	
Minor NCD	46 (26%)		37 (38%)	
No NCD	53 (30%)		5 (5%)	
MMSE (out of 30)	25 [21, 28]	12-30	23 [21, 27]	12-30

Abbreviations. NCD = neurocognitive disorder; MMSE = Mini-Mental State Examination.

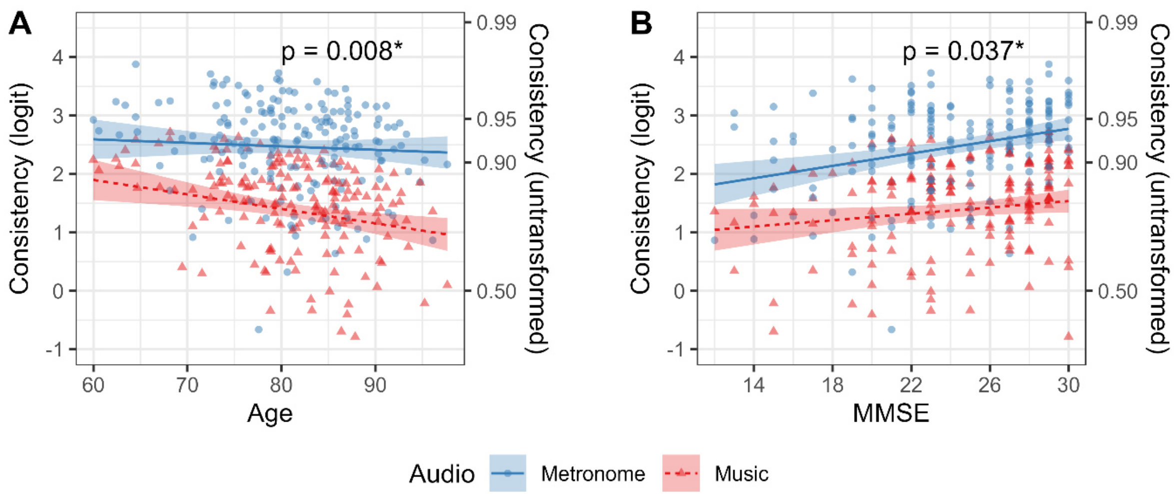
4.1. Model 1

<u>Consistency</u>. This model, which included all 177 patients, revealed main effects of audio (F = 514.75, p < .001) and social context (F = 15.20, p < .001) and an interaction of audio and social context (F = 15.35, p < .001; Supplementary Figure 1). Post hoc tests, adjusted for multiple comparisons using the Benjamini-Hochberg method, indicated lower consistency when tapping with music compared to a metronome in both social contexts (both p < .001). Notably, during music trials, consistency did not depend on social context (p > .05) but during metronome trials, consistency was lower with a live musician than with a video (p < .001). Furthermore, we

identified a main effect of age (F = 4.80, *p* < .05) and a significant interaction of audio and age (F = 7.10, *p* < .01; Figure 1A), indicating a decline of consistency with age specifically in the music conditions. Finally, the model revealed a significant main effect of MMSE (F = 10.68, *p* = .001) and an interaction between audio and MMSE (F = 4.38, *p* < .01; Figure 1B). Contrary to the age effect, our findings suggest that tapping with a metronome was more sensitive to cognitive status, with people with lower MMSE scores demonstrating lower consistency specifically in the metronome conditions.

Figure 1

Tapping consistency depicted against type of audio and age (A), or MMSE (B) (Model 1, N = 177)



Data points depict raw data whereas the regression lines and confidence intervals are derived from the estimated model.

Abbreviation: MMSE = mini-mental state examination

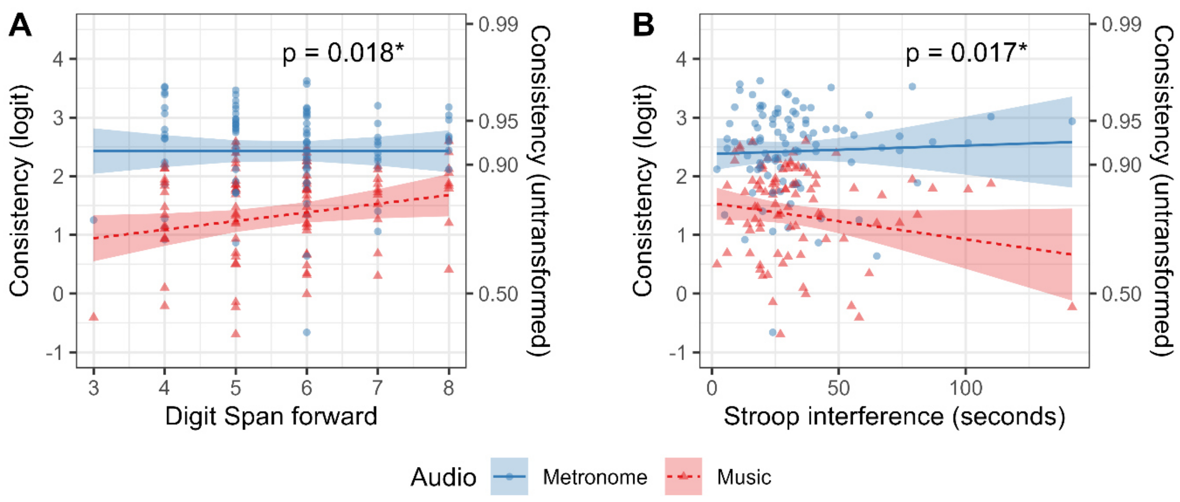
Asynchrony. The model revealed main effects of audio (F = 399.31, *p* < .001), social context (F = 46.89, *p* < .001) and an interaction of audio and social context (F = 27.38, *p* < .001). There was no other significant effect.

4.2. Model 2

Consistency. An additional analysis was conducted using the variables Digit Span forward, Digit Span backward, and Stroop interference (N = 97). As in the previous analysis, the model revealed significant effects of audio (F = 241.42, $p < .001$), social context (F = 5.60, $p = .019$), and an interaction of audio and social context (F = 14.52, $p < .001$). Moreover, we identified significant interactions between audio and Digit Span forward (F = 5.43, $p = .021$; Figure 2A) and between audio and Stroop interference (F = 5.40, $p = .02$; Figure 2B). Tapping consistency with music decreased particularly among people with low scores on the Digit Span forward test, or those who needed more time to resolve the inference in the Stroop test. This trend was not observed in consistency of tapping with a metronome. No significant effects were observed for age, Digit Span backward, or any other interaction effects.

Figure 2

Tapping consistency depicted against type of audio and Digit Span forward (A), or Stroop interference (B) (Model 2, N = 97)

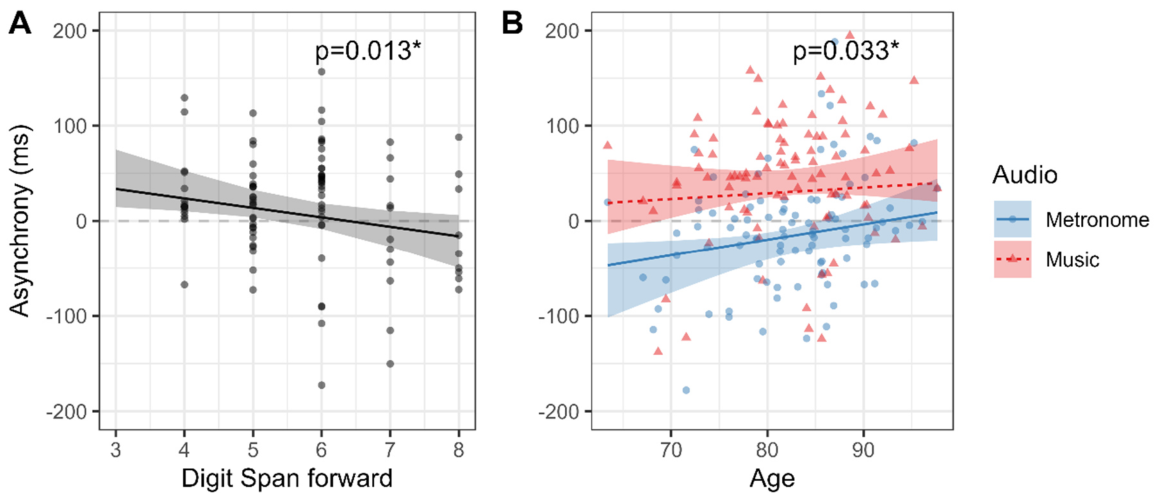


Data points depict raw data whereas the regression lines and confidence intervals are derived from the estimated model.

Asynchrony. The second model including the variables Digit Span forward, Digit Span backward, and Stroop interference (N = 97) revealed significant effects of audio (F = 227.04, $p < .001$), social context (F = 34.43, $p < .001$), and an interaction of audio and social context (F = 12.84, $p < .001$). Moreover, we identified a significant effect of Digit Span forward (F = 6.47, $p < .05$; Figure 3A), and an interaction between audio and age (F = 4.58, $p < .05$; Figure 3B) When tapping with a metronome, people's taps tended to anticipate the beats, and this negative asynchrony was more pronounced in younger individuals.

Figure 3

Tapping asynchrony depicted against Digit Span forward (A), and against type of audio and age (B) (Model 2, N = 97)



Data points depict raw data whereas the regression lines and confidence intervals are derived from the estimated model.

5. DISCUSSION

The objective of this study was twofold. First, we aimed to replicate the previously observed effects of age, MMSE, and type of audio stimulus[12], as well as social context[20], in a larger sample of older adults with and without NCD. The second goal was to examine more specific cognitive mechanisms and their relationship with sensorimotor synchronisation. Of particular interest were the influence of short-term and working memory (assessed by the Digit Span forward and backward tests), as well as inhibition (measured through the Stroop test), on these synchronisation dynamics. We used a comfortable tempo, which was validated through the assessment of individuals' spontaneous motor tempo. Our findings revealed that synchronisation consistency was influenced by MMSE during tapping with a metronome. Conversely, when participants synchronised with a musical stimulus, consistency was associated with age in Model 1, associated with the Digit Span forward test, and associated with performance on the Stroop test in Model 2, conforming to our hypotheses.

When participants synchronised with a musical stimulus, consistency was associated with age, an effect that was not present when participants synchronised with a metronome. This is in line with our previous study[12] and with prior research indicating that the ability to tap with a metronome is preserved with age, although our study stands out as one of the first to investigate sensorimotor synchronisation with music and metronomes in the latest decades of life. Indeed, few studies have investigated the effect of age on tapping with a musical stimulus[28–33]. Moreover, we observed an effect of age on asynchrony to metronome exclusively in model 2. This model included participants who underwent a full memory evaluation due to reported memory deficits. Therefore, our findings suggest that age impacts asynchrony when tapping to a metronome only in patients with more advanced cognitive deficits, suggesting an interaction between NCD and age on asynchrony. Additionally, global cognitive impairment as measured by the MMSE appeared to be associated with a decrease in synchronisation consistency specifically when people tapped with a metronome. This is a novel finding compared to some studies that also used metronomic stimuli but found an effect of NCD only during synchronisation at very fast[30] or slow[31,34] rates, or during continuation tapping after an external sequence ended[31]. More broadly, the observed dissociation, with age affecting music tapping and MMSE affecting metronome tapping, represents a new observation. Interestingly, the interaction of audio and age was only observed in Model 1, which suggests that in Model 2, short-term memory and inhibition may account for some of the variability previously explained by age.

Individuals with higher scores on the Digit Span forward test demonstrated higher consistency when synchronising with music, whereas there was no relationship between Digit Span forward and consistency with a metronome. There was also a global effect of the Digit Span forward test on asynchrony, with larger anticipation associated with higher scores. The Digit Span test assesses the ability to retain items in a storage to reproduce them. Analogously, synchronisation to music may require keeping a representation of its rhythmic structure in short-term memory to internalise its regular beat. Alternatively, the absence of an effect of short-term memory on consistency when tapping with a metronome may reflect a ceiling effect. A previous study[35] has found performance on the Digit Span test to be predictive of rhythmic ability, albeit on a task where participants listened to and then reproduced a rhythm, a task arguably more directly reliant on short-term memory. Overall, our identified contribution of short-term memory to synchronous tapping is novel, especially in this age group.

In addition to short-term and working memory, this study suggests an involvement of inhibition in synchronisation to music. People who were faster in resolving the inference inherent in the Stroop task, an activity thought to rely on inhibitory control, produced taps with a higher consistency when tapping with music. Inhibitory control provides a mechanism whereby competing inputs or actions can be suppressed[36]. Despite the fact that many people effortlessly synchronise to a musical beat, even when beats do not correspond to prominent musical events[37,38], individuals might nonetheless be tempted to, for example, tap along with every note of the melody as opposed to the music's regular beat. In such cases, the ability to exercise inhibition might be instrumental, leading the synchroniser to focus on the regular pulse, induce the beat, and refrain from tapping to other events. Indeed, a recent study[39] involving children also found inhibition (measured by a Go/No Go task) to be related to paced tapping with music, but not with a metronome. Another study[2] found low beat trackers to perform worse on an inhibition test than high beat trackers.

In short, MMSE appeared to be especially predictive of synchronisation with a metronome, whereas short-term memory and inhibition were more strongly associated with synchronisation with music. This suggests that short-term memory and inhibition are less involved in motor control and rather relate to perception, and more specifically, beat induction. Conversely, there may be another mechanism captured by the MMSE that affects beat maintenance. Potential candidate mechanisms include attention, concentration, and the ability to understand and follow instructions[40,41]. The observation of greater consistency in metronome tapping compared to music supports the idea that metronome tapping predominantly involves more automatic beat maintenance.

Finally, the study explored the effect of synchronising with a live person, involving interaction with a musician, vs. a virtual condition, using a video recording of the same musician, as detailed in a separate article[20]. Using a larger sample, we replicate the interaction of audio and social context we already identified in the previous article. Specifically, in the metronome condition, people performed better in front of a video than with a live person, an effect not observed in the music condition.

This study used two types of auditory stimuli: a folk song with some degree of syncopation and a metronome. It should be acknowledged that conclusions drawn about the differences between music and metronome synchronisation are specific to the particular music piece used here, and, among other features, the complexity of its rhythm. Future studies should diversify by incorporating different pieces with varying levels of beat complexity to further explore mechanisms of beat perception and synchronisation. Additionally, replicating the task with purely auditory stimuli would be interesting to determine if the current results generalise to that situation. Overall, continued research into how people engage with music, including listening context, synchronisation dynamics, and musical features, is essential for developing interventions that are not only pleasant and stimulating but hold significant potential for rehabilitation by engaging brain and cognitive mechanisms that underlie both rhythmic and cognitive abilities.

5.1. Concluding remarks

It has been suggested[42–44] that music-based interventions for NCD may be particularly effective if they engage rhythmic synchronisation. This idea is supported by the observation that interventions encouraging active participation appear to yield greater behavioural and psychological benefits compared to those where patients listen passively[45,46]. To optimise the use of interventions relying on rhythmic synchronisation in rehabilitation, a comprehensive understanding of how NCD affects different cognitive domains is needed, as well as of how different cognitive abilities are involved in rhythm perception and production during the latest decades of life. This knowledge is crucial not only for tailoring exercises to specific neurological profiles, but also for recognising how stimulating rhythmic synchrony can be used to enhance cognitive abilities. For example, individuals with frontotemporal NCD may be more impaired in inhibition than other types of NCD, whereas memory may be particularly affected in AD[16]. Therefore, different types of music with different levels of rhythmic complexity might yield different outcomes for different cognitive profiles. Ultimately, considering a patients' cognitive profile is imperative when proposing an intervention. In this research, we established a connection between synchronisation to music and both short-term memory abilities and inhibition. While causality must be established in future interventional studies, our results lend credence to the possibility of stimulating cognitive abilities through music-based interventions incorporating rhythmic synchronisation for rehabilitation purposes.

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During the preparation of this work, the authors used the large language model ChatGPT, version 3.5 (Open AI, 2024), to improve the flow and readability of the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

6.1. Conflicts of interest

The authors have no conflict of interest to report.

6.2. Author contributions

Matthieu Ghilain and Séverine Samson conceived and designed the study. Matthieu Ghilain collected the data, under the guidance and supervision of François Puisieux and Dominique Huvent-Grelle. Lise Hobeika and David Poirier-Quinot significantly contributed to data extraction and processing. Andres von Schnehen analysed the data and wrote the original draft of the paper. Lise Hobeika, David Poirier-Quinot, Dominique Huvent-Grelle, and Séverine Samson were involved in writing and editing the manuscript. Séverine Samson was responsible for acquiring funding.

6.3. Sponsor's role

Funders were not involved in the design or execution of the study, nor in the collection, management, analysis, or interpretation of the data. They also did not participate in the preparation, review approval of the manuscript, or in the decision to submit the manuscript for publication.

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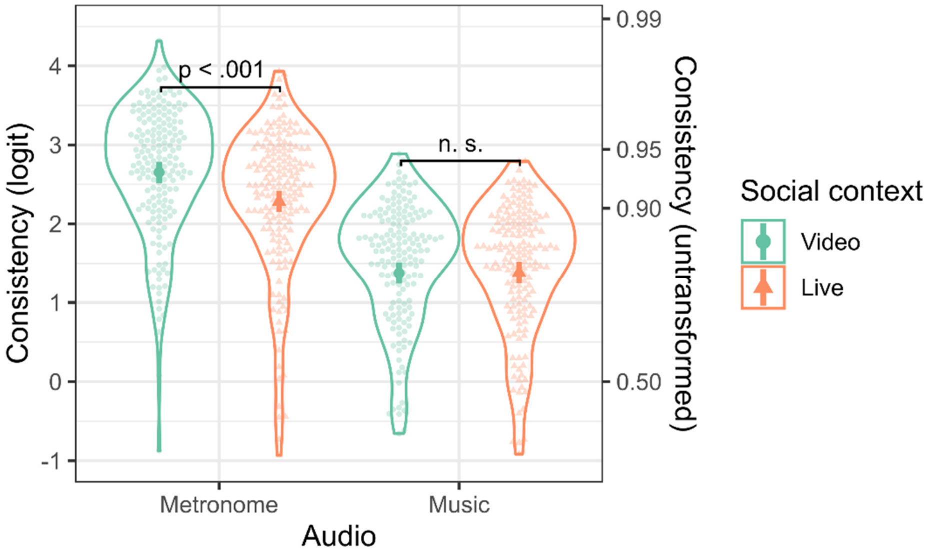
8. SUPPLEMENTARY MATERIAL

Supplementary Figure 1

Effects of audio and social context on tapping consistency (Model 1, N = 177)



Chapter 7

Inhibitory deficits and beat synchronization in older adults

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Abstract

Designing music-based interventions for individuals with neurocognitive disorders, such as Alzheimer's disease, requires an understanding of the interplay between cognitive and rhythmic abilities in aging. This study examined predictors of performance on a sensorimotor synchronization task in which people tapped to metronomes and music with varying beat saliency. In a first analysis involving 84 geriatric day hospital patients, findings revealed that global cognitive impairment and inhibitory deficits were predictive of poorer synchronization, especially with lower beat saliency. A second analysis, with a subset of 57 patients, additionally incorporated measures of beat perception and spontaneous motor variability. They both predicted tapping performance, increasingly so with lower beat saliency. Global cognitive impairment was no longer significant, while inhibitory deficits remained a significant predictor. This highlights the importance of specific cognitive functions, particularly inhibitory control, in successful sensorimotor synchronization in individuals with neurocognitive disorders. Future research should explore rhythm-based interventions to potentially stimulate inhibitory control in neurocognitive disorder.

Introduction

Neurocognitive disorder (NCD), or dementia, refers to a group of conditions marked by a decline in cognitive functioning, affecting memory and other cognitive domains and impacting patients' ability to live independently (American Psychiatric Association, 2013). Despite these impairments, certain abilities such as sensorimotor synchronization (SMS) - the ability to coordinate rhythmic movement with an external beat - appear to be relatively unimpaired. This observation has led to the assumption that activities like dancing, bobbing one's head or tapping one's hands to music might be enjoyed successfully by people with NCD. Therefore, music-based interventions have been suggested under the premise that engaging in music-induced movement would not only be pleasurable but also easy for the patient.

However, this conclusion may be overly simplistic. Much of the literature suggesting intact SMS despite cognitive decline has relied on limited experiments where participants tapped their fingers to simple, evenly spaced tones (i.e., metronomes) (von Schnehen et al., 2022). In contrast, music presents a much more complex stimulus. In music, the beat is not necessarily contained in the acoustic signal; rather, it may be thought of as a cognitive response to music (London, 2004). Synchronizing with music involves internally generating a beat based on periodicities at multiple nested time scales (Puyjarinet et al., 2017) and requires general cognitive processing (Fiveash et al., 2022). Therefore, it is plausible that synchronizing to music relies more on cognitive abilities than previously assumed, but research in this domain is lacking.

Importantly, even if we observe that synchronizing to music depends on intact cognitive function, this does not negate the potential of rhythm-based interventions for this patient group. On the contrary, engaging in rhythmic activities may hold promise for stimulating affected cognitive domains. Improved cognitive function has been demonstrated in lifelong musicians (Hanna-Pladdy & MacKay, 2011) and as a result of music-based interventions in healthy older adults (Marie et al., 2023), although this remains to be explored in people with NCDs.

A few studies (Bangert & Balota, 2012; Hobeika et al., 2022; Martin et al., 2017; von Schnehen et al., 2024) have suggested that the severity of cognitive decline related to NCDs is associated with performance on SMS tasks. As a first step, those studies linked SMS performances to diagnostic categories or general screening tools such as the Mini-Mental State Examination (MMSE). To better comprehend the cognitive processes underlying SMS to music, it is imperative to move beyond a single score indicating overall cognitive impairment. A key cognitive mechanism to consider is inhibition, which has been linked to beat perception and motor performance (Bégel et al., 2022; Puyjarinet et al., 2017), albeit not yet in elderly populations or those with NCD. We recently demonstrated (**Chapter 6**) that inhibition as measured by the Stroop test was related to tapping performance when individuals synchronized with music, but not with a metronome. However, using only two stimuli limits the ability to make definitive conclusions about the role of inhibitory control in music synchronization. The saliency of a beat can vary substantially both between and within musical pieces, depending on the extent to which music features repetitive rhythmic patterns with regular intervals and pronounced accents (Toiviainen et al., 2020). It remains unclear whether any musical stimulus necessitates inhibitory control for synchronization, or if the involvement of inhibition is proportional to the saliency of a beat.

Successful SMS requires at least three key abilities: perceiving a beat, producing a regular motor response, and coupling this motor response with auditory input (van der Steen & Keller, 2013). To better understand the nature of sensorimotor impairment, it is beneficial to include a task that assesses perceptual judgements in the absence of a motor response, and conversely, a measure of self-paced motor production without an external stimulus. Such assessments have seldom been conducted in the literature on SMS and NCD.

In this study, we aim to extend our previous result with four key modifications: (1) employing an SMS (hand tapping) task in which we manipulate beat saliency; (2) using the Beat Alignment Test (BAT) (Dalla Bella et al., 2017; Iversen et al., 2008) as a measure of beat perception; (3) calculating the variability of spontaneously produced taps; and (4) administering a test of inhibition, namely, an adaptation of the Go/No-go task from the Frontal Assessment Battery at Bedside (Dubois et al., 2000). As a first hypothesis, we expected synchronization consistency to be lower with music than with a metronome, like in previous studies (Ghilain et al., 2020; Sowiński & Dalla Bella, 2013). Between the two musical stimuli, we expected the lowest synchronization consistency with the stimulus that had lower beat saliency, as the presence of a clear pulse in the acoustical signal is associated with an improved ability to synchronize to a beat (Bégel et al., 2018). Secondly, we expected an interaction between beat saliency and MMSE, where synchronizing with a stimulus lower in beat saliency would depend more on overall cognitive functioning. Thirdly, we anticipated an interaction between beat saliency and Go/No-go, suggesting that the involvement of inhibition control would be greater in conditions with lower beat saliency. Fourth, we expected an interaction between beat saliency and BAT, such that beat perception abilities would be more critical for successful synchronization as the beat becomes less salient. Finally, we expected an interaction between beat saliency and CV(SMT), indicating that tapping would increasingly rely on motor variability as beat saliency decreases.

Methods

Participants

Eighty-six French-speaking patients were recruited from Lille University Hospital during scheduled consultations for memory problems or falls. None of them reported uncorrected hearing or vision problems that precluded their participation. One participant was unable to perform the synchronization task due to pain in their right arm, and another participant's tapping data were lost due to a technical error, leaving the data from 84 participants to be analyzed. The data were collected between October 2023 and February 2024. All participants provided informed consent following the Declaration of Helsinki.

Apparatus and stimuli

For spontaneous and paced tapping tasks, the experimental setup included a chair with a tablet attached to its right armrest, on which the patient tapped their right hand using a ball-like probe (Desmet et al., 2017; Lesaffre et al., 2017). Stimuli were presented and tapping responses were collected using a program written in MAX/MSP. Participants were seated across a screen, which was only used to provide instructions before the task and during a practice trial. During the experiment, the screen remained blank. A curtain separated the participants from the experimenter to minimize potential distractions and interactions that could influence the participants' performance.

Musical and metronome stimuli were 60 seconds long with a 600 ms inter-beat interval, each trial preceded by a 4-beat intro. The musical stimuli were instrumental without vocals. For high beat saliency music, we used an excerpt from the track "Joyful Acoustic Ukulele" by Seastock, available for download at https://www.jamendo.com. This track has been annotated by musicians as having very high rhythmic stability and low rhythmic complexity (Aljanaki et al., 2017). To corroborate these ratings, we estimated pulse clarity using *MIRtoolbox*

(Lartillot & Toiviainen, 2007) in MATLAB (The MathWorks Inc, 2022) as an additional metric of beat saliency, resulting in a very high pulse clarity of 0.93. The low beat saliency music was an excerpt from the track "Shaving Mirror" by Kevin MacLeod, available at https://incompetech.com, which was previously validated, demonstrating relatively low vector length and high perceived tapping difficulty (for details, see Jamey et al., 2024). This track's tempo was manipulated with Ableton Live 11 to match the 600 ms inter-beat interval. *MIR*toolbox estimated a relatively low pulse clarity of 0.32 for this track. Finally, the metronome sequence was of the same length and included regular beats at the same tempo as the musical stimuli.

An adapted version (Dalla Bella et al., 2017) of the BAT, implemented on a tablet device, was used to assess listeners' ability to detect deviations from the beat. In each of 24 trials, musical examples were presented (two different fragments from Bach's *Badinerie* and Rossini's *William Tell Overture*), with an inter-beat interval of 750 ms, onto which a sequence of isochronous tones was superimposed after a few beats. Participants had to determine whether the tones aligned with the music or not.

Procedure

Participants first underwent a brief assessment of musical sophistication using an orally administered version of the French translation (Degrave & Dedonder, 2019) of the Goldsmiths Musical Sophistication Index (Gold-MSI) (Müllensiefen et al., 2014). This questionnaire assesses musical experience as a multi-faceted concept including formal musical training but also informal engagement with music. Next, they were instructed to tap spontaneously at their preferred, comfortable rate for 31 taps (30 inter-tap intervals). Subsequently, participants engaged in the Go/No-go task. In this task, participants tapped a pen on a table following instructions that changed midway. In the first half, participants were instructed to tap twice whenever the experimenter tapped once, and once whenever the experimenter tapped twice. In the second half, participants had to tap once when the experimenter tapped once, and not move when the experimenter tapped twice, thus requiring them to inhibit a response (Dubois et al., 2000).

Participants then underwent the synchronization task, during which they synchronized their tapping to musical and metronomic stimuli. After a practice trial, participants completed six experimental trials, consisting of two repetitions of each type of auditory stimulus, which were counterbalanced and presented in a randomized order. Finally, they engaged in the BAT.

Independent of their participant in the current study, patients also underwent a global cognitive assessment. This included the MMSE for most participants, while others underwent the Montreal Cognitive Assessment (Nasreddine et al., 2005) instead. Their scores were converted to MMSE equivalents using equipercentile equating (Roalf et al., 2013).

Data analysis

Two participants did not complete the Gold-MSI, thus their scores were imputed by taking the average of all other participants.

We computed spontaneous motor tempo (SMT) as the mean length of the inter-tap intervals in the spontaneous tapping task, after excluding the first eight and last two taps, and its coefficient of variation (CV(SMT)), as a measure of spontaneous tapping variability.

The sensitivity index *d'* for the BAT, a measure of perceptual beat tracking sensitivity, was computed as the difference between z-transformed hits and false alarms, whereby higher values reflect higher performance. For the synchronization task, consistency was computed using circular statistics (Fisher, 1995) with the CircStat toolbox (Berens, 2009) in MATLAB and logit-transformed to reduce data skewness (Falk et al., 2015). Asynchrony was also computed using circular statistics, but only to identify and remove all observations in which asynchrony was below -135° or above 135° relative to the beat, indicating tapping in antiphase. This resulted in the removal of 2.6% of observations.

Two linear mixed-effect model analyses were conducted, both with consistency as a dependent variable. Model 1 examined the role of global cognitive impairment and inhibition in the full sample (N = 84), while Model 2 additionally included the factors beat perception and motor variability in a subset of participants (N = 57) due to missing data: For the BAT, data from one participant were lost due to a technical problem, 15 participants wished to discontinue the study during or before this task, five were deemed ineligible or did not comprehend the instructions, and three participants were unable to participate due to timing constraints beyond our control. For the spontaneous tapping task, an error in the recording script resulted in the loss of data from five participants.

Both models included the random effect participant and the fixed effects beat saliency (metronome, high-beat saliency music, and low-beat saliency music), MMSE, Go/No-go, and the interactions between beat saliency and MMSE, and beat saliency and Go/No-go. Model 2 additionally contained the BAT score, CV(SMT), and the interactions between beat saliency and these two variables. For both analyses, diagnostic plots were inspected for violations of the assumptions of homoscedasticity, normality of residuals, multicollinearity, and outliers, and no violations were detected. Effect sizes were calculated as f^2. Statistical analyses were performed in R (R Core Team, 2024).

Results

Table 1 presents demographic and clinical characteristics of the participants included in the two models. Among the 26 participants with major NCD included in Model 1, eight were diagnosed with Alzheimer's disease, five with vascular NCD, 11 with mixed-etiology NCD, and two with NCD with Lewy bodies. In Model 2, of the 13 participants with major NCD, three were diagnosed with Alzheimer's disease, two with vascular NCD, seven with mixed-etiology NCD, and one with

NCD with Lewy bodies. Participants' mean spontaneous motor tempo was 671 ms (SD = 297 ms). Distributions of age and MMSE in the current sample can be found in Figure 1.

Table 1

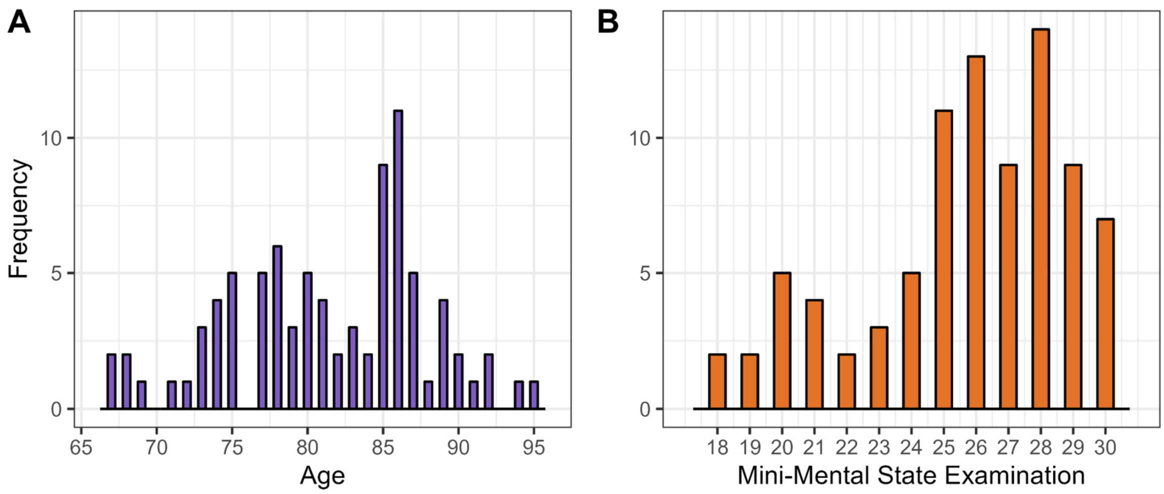
Participant characteristics in the two models

	Model 1 (N = 84)		Model 2 (N = 57)	
	Median [first quartile, third quartile] or frequencies (%)	Range	Median [first quartile, third quartile] or frequencies (%)	Range
Age	81 [77, 86]	67-95	81 [75, 85]	67-92
Gender	56 women (67%)		40 women (70%)	
Years of education	11 [7, 15]	5-20	11 [7, 15]	5-20
Gold-MSI	48 [41, 52]	19-71	48 [40, 53]	24-71
Diagnosis				
Major NCD	26 (41%)		13 (30%)	
Minor NCD	33 (51%)		26 (60%)	
No NCD	5 (8%)		4 (9%)	
MMSE	26 [24, 28]	18-30	27 [25, 29]	18-30

MMSE = Mini-Mental State Examination

Figure 1

Distributions of age and scores on the Mini-Mental State Examination in the full sample (N = 84)



MMSE = Mini-Mental State Examination.

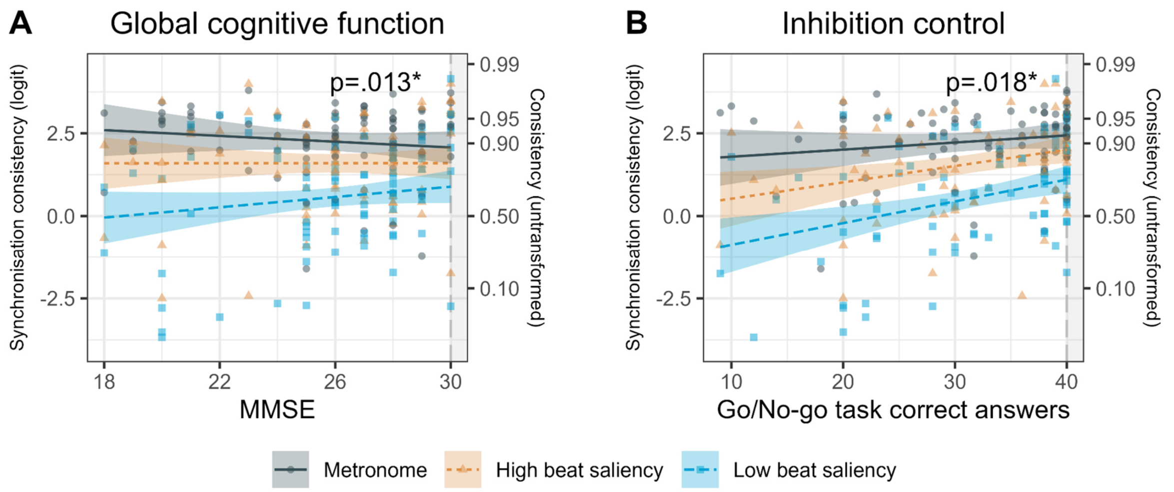
Model 1: effect of inhibition and global cognitive functioning

Model 1 included the full sample of 84 patients but comprised only beat saliency, MMSE and Go/No-go as variables of interest. There was a significant main effect of beat saliency, $F(2, 390.71) = 98.05$, $p < .001$, $f^2 = 0.21$ and a significant interaction between beat saliency and MMSE, $F(2, 390.35) = 4.39$, $p = .013$, $f^2 < 0.01$ (Figure 2A). A post hoc test using pairwise comparisons of the slopes of the regression lines for each level of beat saliency against each other, corrected for multiple testing using the Bonferroni method, revealed that the slope for low beat saliency was more positive and significantly different from the slope for MMSE ($p = .011$). Neither slope was significantly different from the slope for the high beat saliency condition. (both *ps* > .05). Additionally, there was a significant main effect of

Go/No-go, $F(1, 80.95) = 8.34$, $p = .005$, $f^2 = 0.05$ and an interaction between beat saliency and Go/No-go, $F(2, 391.44) = 4.04$, $p = .018$, $f^2 < 0.01$ (Figure 2B). A post hoc test, corrected for multiple testing using the Bonferroni method, revealed, again, that the slope for low beat saliency was more positive and significantly different from the slope for MMSE ($p = .016$), whereas neither slope was significantly different from the slope for the high beat saliency condition. (both *p*s > .05). The main effect of MMSE was not significant. The model was tested against the demographic variables age, gender, years of education, and Gold-MSI, but none of their effects were significant and their inclusion did not change the results of the model.

Figure 2

Synchronization consistency in relation to beat saliency, MMSE (A) and participants' scores on the Go/No-go test (B) in Model 1 (N = 84)



Note. Consistency was logit-transformed before inclusion in the model; however, the corresponding untransformed values are provided on the secondary y-axes for reference. The gray shaded area indicates the highest possible scores: 30 for the MMSE and 40 for the Go/No-go task. MMSE = Mini-Mental State Examination.

Model 2: Effects of beat perception and motor variability

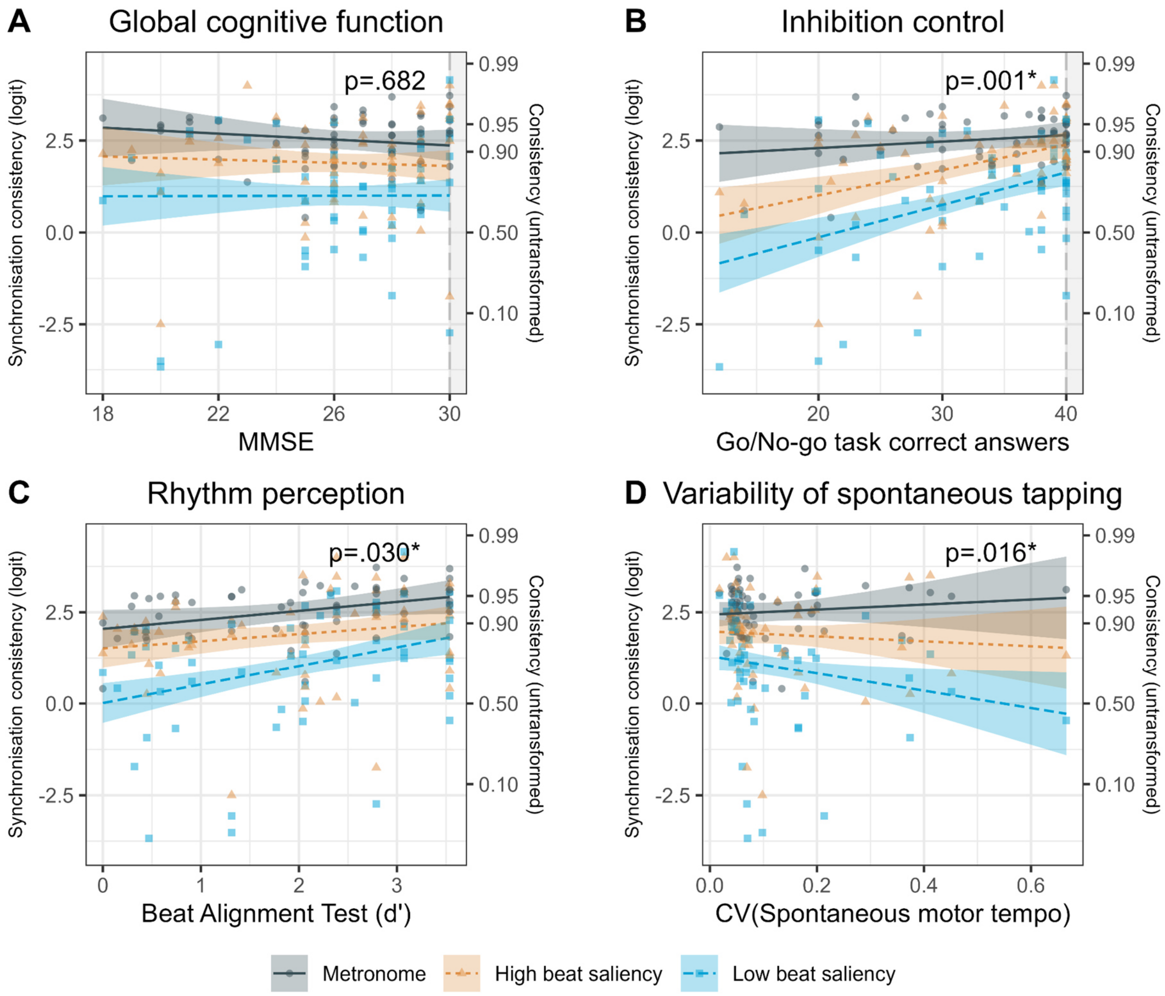
A second model was run that additionally included the variables BAT and CV(SMT), resulting in a smaller sample size ($N = 57$) due to missing data for these variables. Unlike in Model 1, the interaction between beat saliency and MMSE was not significant in this model (Figure 3A). Significant effects included a main effect of beat saliency, $F(2, 266.44) = 64.53$, $p < .001$, $f^2 = 0.25$, a main effect of Go/No-go, $F(1, 52.51) = 16.22$, $p < .001$, $f^2 = 0.12$), an interaction between beat saliency and Go/No-go, $F(2, 267.52) = 7.59$, $p = .001$, $f^2 = 0.03$ (Figure 3B), a main effect of BAT, F(1, 52.00) = 10.23, p = .002, f^2 = 0.07 an interaction between beat saliency and BAT, $F(2, 267.01) = 3.55$, p = .030, f^2 = 0.01 (Figure 3C), and an interaction between beat saliency and CV(SMT), $F(2, 265.43) = 4.23$, p = .016, f^2 = 0.02 (Figure 3D). The main effects of MMSE and CV(SMT) were not significant. As with Model 1, this model has been tested against the demographic variables age, gender, education, and Gold-MSI, but none of these variables were significant or changed the results of the model.

To further explore the three significant interactions, the slopes of the regression lines of each level of beat saliency were compared against each other, using pairwise comparisons, corrected for multiple testing using the Bonferroni method. For the interaction between beat saliency and Go/No-go, the regression slope for metronome was different (i.e., less steep) from the slopes of both music conditions (both ps $< .05$), which were not different from each other (p = .894). This suggests that synchronizing with music, regardless of beat saliency, depends on inhibition control. In contrast, for the interaction between beat saliency and BAT, only the slopes for the two music conditions were different from each other, with the one for low beat saliency being steeper (p = .039), whereas the other two comparisons did not yield significance (both ps $> .05$). This indicates that rhythm perceptual ability is particularly crucial for synchronizing to music with low beat saliency. Finally, for the interaction between beat saliency and CV(SMT), only the slope for metronome and for music with low beat saliency were different from each other (p = .012), whereas the other comparisons were not significant (both ps

> .05). This suggests that motor variability is particularly involved in tapping to music with an unclear beat.

Figure 3

Synchronization consistency in relation to beat saliency, MMSE (A), performance on the Go/No-go test (B) and on the Beat Alignment Test (C), and to variability of spontaneous tapping (D) in Model 2 (N = 57)



Note. Consistency was logit-transformed before inclusion in the model; however, the corresponding untransformed values are provided on the secondary y-axes for reference. The gray shaded area indicates the highest possible scores: 30 for the MMSE and 40 for the Go/No-go task. MMSE = Mini-Mental State Examination; CV = coefficient of variation.

Discussion

The primary objective of this study was to investigate the effects of global cognitive impairment and inhibition control on SMS to auditory sequences with varying levels of beat saliency. Recent research has identified a role of global cognitive impairment (Hobeika et al., 2022; von Schnehen et al., 2024), and of inhibition (**Chapter 6**) in SMS. Building on this, we manipulated beat saliency by using three levels to test if the previously identified effects of cognitive impairment and inhibition on SMS would interact with the difficulty of perceiving a beat in music. By including measures of pure beat perception (without motor response) and spontaneous tapping variability (without auditory input), we sought, firstly, to determine if these mechanisms themselves are affected by impaired cognition or inhibition. Secondly, their inclusion in the model allowed us to determine if cognitive function and/or inhibition independently contribute to SMS, that is, to mapping a motor response to a perceived beat, beyond their potential roles in beat perception and/or motor initiation.

In a first analysis, we found that both global cognitive impairment and inhibition control were associated with SMS consistency, with their influence moderated by beat saliency. Specifically, lower beat saliency was related to the associations of consistency with MMSE and Go/No-go test score. However, the first model only considered SMS, which is the result of at least three processes (perceiving a beat in a complex signal; producing a regular motor response; and mapping the latter to the former). Adding specific measures of beat perception and motor variability to this second model allowed us to test whether cognitive impairment and/or inhibition specifically impact this auditory-motor mapping process. Interestingly, in this model, the effect of MMSE, the test for global cognitive decline, was no longer significantly related to successful synchronization. However, inhibition control, as well as its interaction with beat saliency, remained significant predictors. This indicates that when beat perception and motor variability are taken into account, global cognitive decline does not explain variance in SMS, whereas inhibition control does.

Furthermore, both beat perception and motor variability interacted with beat saliency in a similar way. Tapping with a metronome appeared relatively automatic and was easily accomplished by all participants, regardless of their level of inhibition control, beat perception ability, or motor variability. Conversely, as the beat became less salient and more difficult to extract, successful synchronization increasingly depended on inhibition control, beat perception, and motor variability. While the roles of beat perception and motor variability in SMS are straightforward, the role of inhibition is less obvious. Inhibition control enables the suppression of competing inputs or actions (Wiecki & Frank, 2013). Inhibition is related to selective attention, and performance on many experimental tasks, as well as navigating the real world, relies on filtering out distracting information to focus on task-relevant information (Van Moorselaar & Slagter, 2020). This is relevant for the current musical task: Inhibition may be involved in directing attention to musical events where a motor response is appropriate, such as notes that coincide with the regular beat, and away from off-beat musical events. Additionally, inhibition may govern the suppression of unwanted motor responses. Previous research in children has shown that tapping with music, and not with a metronome, is related to inhibition (Bégel et al., 2022); our study is the first to demonstrate this in a sample of older adults across later decades of life, a demographic often underrepresented even in geriatric research, and across varying levels of cognitive impairment.

Our study's use of three levels of beat saliency (including a metronome as the highest saliency level) marks a significant improvement over previous SMS research, which often used metronomes as the only stimuli to synchronize to (von Schnehen et al., 2022). However, future research should employ a larger set of musical stimuli to represent the spectrum of beat saliency even better, approximating how people interact with music in the real world.

The current study confirms the assertion that beat perception and SMS are tightly linked (Dalla Bella et al., 2017, 2024; Fujii & Schlaug, 2013; Iversen et al., 2008; Puyjarinet et al., 2017; Tranchant et al., 2021). This is consistent with findings that rhythm perception, even in the absence of movement, activates motor areas in the brain (Chen et al., 2008; Grahn & Brett, 2007). Our research adds the dimension of beat saliency, showing increased reliance on rhythm perception abilities when beat saliency is low. Finally, it demonstrates the importance of controlling for beat perception and motor variability.

This study contributes to the growing body of research highlighting the connections between cognitive and rhythmic abilities (Bailey & Penhune, 2010; Puyjarinet et al., 2017). Given the increasing understanding of these relationships and the observed cognitive benefits of music training in healthy older adults (Marie et al., 2023), future research should explore the effects of music-based interventions on cognitive rehabilitation in individuals with NCD. Specifically, interventions that stimulate rhythmic movement, require beat extraction, or involve increasing levels of beat complexity, should be explored.

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Chapter 8

Discussion

In this PhD thesis, I aimed to shed light on the mechanisms that influence how older adults move in synchrony with external rhythms. Understanding these mechanisms is important for developing interventions to improve quality of life in this population. To explore this topic, I first conducted a literature review, followed by four experimental studies. In the following, I will integrate the results of these studies, discuss their implications for theory and practice, and propose future research to further advance our understanding of sensorimotor synchronization (SMS) in aging populations.

In the literature review, we found that sensorimotor synchronization (SMS) is an ability that is generally preserved in both healthy aging and individuals with neurocognitive disorder (NCD), particularly when tapping to a simple rhythm at a comfortable tempo. However, age-related or NCD-related differences in performance might emerge in tasks that used very fast or slow tempi, continuation of sequences after the auditory stimulus had ceased, or while engaging in a concurrent cognitively demanding task. These differences may be more pronounced in individuals over 75 years old or those with more severe NCDs.

Our review (**Chapter 2**) also highlighted significant gaps in SMS research. There are few studies investigating SMS abilities in NCD, especially in those at a moderate to severe stage of the disorder. Additionally, there is a scarcity of studies using real music as stimuli, despite the fact that many studies claim to be relevant for engagement with music in the real world. Finally, during the review, we could only speculate on the cognitive mechanisms that would, on the one hand, be impacted in healthy aging and NCD, and that would in turn affect an individual's ability to synchronize their movement with music or other stimuli.

Our four experimental studies all used the hand-tapping paradigm to investigate SMS in healthy aging and NCD. The studies presented in **Chapters 4 and 5** employed stimuli with tempo changes to test whether adaptation to them would be affected by age and/or NCD. **Chapters 6 and 7** focused on specific cognitive mechanisms, namely, short-term memory and inhibition, to go beyond the global effect of cognitive impairment on SMS. The final study in **Chapter 7** additionally examined the influence of beat saliency on synchronization performance as well as measures of beat perception and motor variability, to test how these factors interacted with each other.

In the following sections, we discuss some effects that we consistently identified across studies, others that may have differed between studies, and we offer some interpretations as to why these differences might have occurred.

Audio type

All four studies identified an effect of audio type on synchronization consistency, with performance being better with a metronome than with music. This phenomenon has been observed previously (Aschersleben, 2002; Dalla Bella et al., 2017; Ghilain, Hobeika, Lesaffre, et al., 2020), but our final study presented in **Chapter 7** extended this observation by using music with varying levels of beat saliency. Consistency was highest with a metronome, followed by high-beat-saliency music, and lowest with low-beat-saliency music. While it is true that synchronizing with music involves the additional task of extracting a beat, we cannot exclude the possibility that under different circumstances, people might display superior synchronization consistency with music than with a metronome. All stimuli in all studies presented here used tempi between 600 ms and 800 ms, which we considered to be comfortable, in accordance with the literature on SMS and aging (McAuley et al., 2006; Vanneste et al., 2001). We also confirmed that the stimulus tempi were indeed comfortable by assessing participants' mean spontaneous motor tempo, which ranged from 680 ms to 744 ms across all four studies described here. It is possible that audio type might interact with tempo, and that at tempi further away from one's comfortable range, music might be easier to synchronize with than a metronome (Rose et al., 2019). Moreover, music contains various elements such as pitch and loudness that may provide cues related to where beats are positioned, so these multiple musical features may aid in synchronization (de Dreu et al., 2014). Yet, at least at a comfortable tempo, it appears that metronomes are easier to synchronize with than music, even in the case of the very high-beat saliency music used in the last study. It should also be mentioned that music is more motivating and rewarding than a metronome. It has been suggested that the reward qualities of music may boost synchronization (Fiveash et al., 2023), leading to more consistent tapping. However, this effect might have been less pronounced in our participants, many of whom had major or minor NCD. Recent research has shown that while healthy older adults display increased positive facial expressions in response to music compared to a metronome during a synchronization task, this effect was absent in people with major NCD (Hobeika et al., 2021, 2022). Future research could assess musical reward directly by using a questionnaire such as the Barcelona Musical Reward Questionnaire (Mas-Herrero et al., 2013).

Regarding asynchrony, all studies that looked at asynchrony (**Chapters 3 through 5**) found a clear effect of a negative asynchrony (tapping ahead of the beat) that was more pronounced when tapping with a metronome than with music. The reasons for this negative mean asynchrony remain unresolved. It is thought that this asynchrony reflects the subjective impression of tapping in synchrony with the pacer (Aschersleben, 2002; Repp, 2005). It is reduced when inter-onset intervals are subdivided (Repp, 2003) which may explain why it is less pronounced with music, where each beat is generally subdivided by many musical events. However, our studies find a negative mean asynchrony also when tapping with music, although it is smaller than with metronomes, challenging the assumption that the negative mean asynchrony only exists with metronomes.

Age

Regarding age, our first three experimental studies (**Chapters 4 through 6**) demonstrated that age might be associated with SMS, but this effect might depend on the type of audio (music vs. metronome). Specifically, older age might be associated with a decrease in synchronization consistency when the stimulus is music. This effect was not observed in the study on healthy younger and older adults (**Chapter 5**); however, it is important to note that the median age of the older participants in this study was 70. In contrast, the studies described in **Chapters 4 and 6**, which did identify an age-related decline in consistency with music, included many participants in their 70s, 80s, and even some in their 90s. Therefore, it appears that an age-related difficulty in extracting a beat from music and synchronizing with it may only emerge in the latest decades of life. This age-related decline might be due to changes with age in auditory processing, cognitive abilities such as attention and working memory, and motor function (Getzmann & Falkenstein, 2011; Grady, 2012; Harada et al., 2013). There remains a need for a single study that includes participants of all ages and that aims to disentangle healthy and pathological aging, while also considering variables such as education and musical expertise, given that the relationship between aging and SMS is multifaceted and dependent on a number of biological and experiential factors.

Mini-mental state examination

Regarding the mini-mental state examination (MMSE) as a measure of global cognitive function, the results were somewhat mixed. In the first experimental study (**Chapter 4**), we observed a main effect of MMSE on consistency, irrespective of audio type. In the third study (**Chapter 6**), we found an interaction between audio type and MMSE, with MMSE scores specifically predictive of tapping to a metronome. Perhaps the difference in results between these two studies may also be attributed to their respective statistical power. The study in **Chapter 4** included 61 participants, whereas the study in **Chapter 6** had 177 participants. It is possible that an interaction effect between audio type and MMSE was present in the former study but did not reach statistical significance due to the smaller sample size.

The most intriguing result emerged in the final study (**Chapter 7**). Initially, an interaction between MMSE and beat saliency was observed: As beat saliency decreased, consistency depended more on cognitive function. Yet, when beat perception and spontaneous motor variability were added to the model, the MMSE effect was no longer significant. This suggests that while MMSE might be related to beat perception and/or motor variability, the mapping of a motor response to a beat may not be as related to global cognitive function as initially assumed. However, it is worth repeating that despite the manipulations introduced in our experimental studies, such as tempo changes and the stimulus with low beat saliency in the last study, the synchronization tasks remained relatively simple across all experiments. As noted, SMS with slower sequence or more cognitively demanding paradigms might still rely more on intact cognitive functioning than the tasks employed here. Finally, the differences in performance and their relationship to MMSE might be influenced by the specific songs used, as the different studies used different musical stimuli. Asynchrony, on the other hand, did not seem to be affected by overall cognitive status.

Cognitive abilities

Our first experimental studies provided valuable insights into how age and cognitive impairment, as measured by the MMSE, might influence SMS to music and metronomes. However, aging is very general physiological process, and the symptoms of NCD are similarly vast, affecting multiple sensory modalities (Armstrong, 2009; Brenowitz et al., 2019; Hardy et al., 2016) and cognitive domains such as attention, memory, cognitive flexibility, language, and social cognition (American Psychiatric Association, 2013).

A critical question of this part of the PhD was to identify the specific cognitive functions central to SMS, which helps determine which types of NCD profiles are likely associated with sensorimotor decline. For the study described in **Chapter 6**, we analyzed previously collected synchronization data (Ghilain, Hobeika, Lesaffre, et al., 2020) and supplemented them with data from neuropsychological tests that the majority of patients in that study had undergone. We found that short-term memory as measured by the Digit Span test (Wechsler, 2008) and inhibition, as measured by the Stroop task (Stroop, 1935), were associated with SMS. To verify this effect, our subsequent study in **Chapter 7** included an additional inhibition test - an adaptation of the Go/No-go task from the Frontal Assessment Battery at Bedside (Dubois et al., 2000) - in the assessment of each participant. Again, we found a significant effect of inhibition on consistency. Importantly, the reliance on inhibition was stronger as the saliency of the beat decreased, and this interaction effect persisted even when measures of beat perception and motor variability were included.

It is interesting to ponder why in **Chapter 6**, we found an association between synchronization consistency and the forward part of the Digit Span test, but not with the backward part. A simplistic interpretation would be that short-term memory affects musical beat synchronization, whereas working memory does not. However, this difference may well reflect psychometric properties of the tests rather than the abilities measured (Strauss, 2001).

While the Digit Span forward and backward tests are thought to assess short-term memory and working memory, respectively (Aben et al., 2012; Banken, 1985; Woodward et al., 1987), research using confirmatory factor analysis has indicated a lack of discriminant validity between the two tests and that indeed, Digit Span forward also measures working memory to some extent (Bowden et al., 2013). Another study reported high reliability for Digit Span forward but low reliability for Digit Span backward (De Paula et al., 2016). Undoubtedly, the backward version of this task is inherently more cognitively demanding than the forward version. In our sample of elderly patients, Digit Span backward scores were concentrated in narrow range, suggesting a floor effect (see Fine et al., 2012, for normative data for healthy adults aged 85 and above, with a considerably higher Digit Span backward and a larger standard deviation than in the current sample). This limited variability likely reduced statistical power, explaining the lack of an observed effect of working memory.

Despite this, working memory may well be involved in rhythmic synchronization, as suggested in previous research (Bailey & Penhune, 2010; Bégel et al., 2022; Chen et al., 2008; Fiveash et al., 2022). Working memory has been linked to SMS with expressively timed music with fluctuating beat clarity, another task where the beat must be actively searched for and induced (Colley et al., 2018). The authors of this study suggested that working memory plays a role in updating temporal intervals that govern musical pulse sequences, facilitating SMS. Thus, our results do not exclude the possibility of a contribution from working memory to SMS.

This work represents a significant advance in understanding the cognitive abilities involved in SMS, particularly in aging and NCD. In the review in **Chapter 2**, we had speculated mostly about the roles of working memory and attention, although we did mention executive functioning, of which inhibition is a part. But only through our experimental studies did we find that inhibition is indeed a key cognitive predictor of SMS. While we did not include a direct test of attention, it remains very likely that attention plays a role in successful synchronization and is involved in the tests we used to measure other cognitive functions, such as the Digit Span, Stroop, and Go/No-go tests.

Musical experience

The study with healthy participants, detailed in **Chapter 5**, was the only one that treated musical experience as a main variable of interest and offered hypotheses about it. In this study, we identified a relationship between participants' scores on the Goldsmiths Musical Sophistication Index (Gold-MSI) (Müllensiefen et al., 2014) and their synchronization consistency, as well as an interaction effect between Gold-MSI scores and audio type on asynchrony. Musical experience thus appears to enhance auditory-motor integration abilities, leading to more consistent responses and reduced asynchrony with the beat, although this effect varies depending on the type of audio stimulus. More precisely, when tapping with music, higher musical sophistication was associated with reduced asynchrony, thus more accurately tapping on the beat. This may suggest music-induced cerebral plasticity.

The other three studies also measured musical experience to some extent, but did not find it to be a predictor of synchronization performance. The studies in **Chapters 4 and 6** inquired about participants' musical training and listening habits by means of an unpublished questionnaire, whereas the study in **Chapter 7** used the Gold-MSI, albeit a version that was orally administered and shorter than the version used in **Chapter 5**. These differing methodologies make inter-study comparisons difficult, but it is interesting to consider the samples recruited in each study.

The studies described in **Chapters 4, 6, and 7** were conducted at a geriatric hospital, where patients were recruited on the spot and participated during breaks between other appointments. As participation was an alternative to waiting, the majority of patients we approached agreed to participate, and most of them were not particularly interested in music. In contrast, the participants in

Chapter 5 were likely more musically inclined, as they specifically went to the university campus to participate in a music-related study. Efforts were made to ensure that the young and older healthy groups in **Chapter 5** had similar levels of musical experience to each other, but overall, they were likely more musically experienced than the participants in the other three studies in the hospital setting.

The difference in recruitment might explain why the effects of musical experience were more evident in the study with healthy individuals. The studies at the hospital possibly had a sample that was too homogeneous in terms of musical experience that any effects of musical experience would be visible. Conversely, the participants in **Chapter 5** might represent a broader spectrum of musical experience, allowing the influence of Gold-MSI scores on both consistency and asynchrony to become apparent.

Gender and education

Although it was not the primary focus of our experimental studies, we collected data on all participants' years of education and included gender and education as adjustment variables in at least one stage of the mixed modes analyses in each study. We did not observe any effects of these variables. Adjusting for education was important because it is generally related to musical expertise and performance (Müllensiefen et al., 2014; Schellenberg, 2006). A gender effect was not expected, especially since participants performed the task in isolation, albeit sometimes with a video recording of a male musician. Gender may have well played a role in interpersonal SMS, where the composition of duos in terms of gender can play a role (Gaggioli et al., 2019).

Adaptation to tempo changes

The first two studies, presented in **Chapters 4 and 5** focused, respectively, on how the severity of neurocognitive disorder (NCD) and age impacted how individuals adapted to tempo changes. To accomplish this, we created sequences in which half of the trials included a sudden acceleration or deceleration every 15 seconds. Using circular statistics, we computed synchronization consistency and asynchrony per 15-second segment. This method was chosen for its robustness against missing or additional taps, which are common in this patient group (Ghilain, Hobeika, Schiaratura, et al., 2020; Hobeika et al., 2022). We then compared performance in segments following a tempo change to those with a stable tempo and tested interactions between tempo stability and other variables such as age and MMSE.

The rationale behind this approach was based on previous observations that while simple SMS with isochronous sequences at a comfortable tempo might be easily accomplished regardless of age and cognitive impairment, more challenging tasks - such as tapping at a very slow rate, continuing to tap after an external sequence ends, or performing a cognitively taxing task while tapping - can reveal age-related and NCD-related deficits in sensorimotor performance (Bangert & Balota, 2012; Krampe et al., 2010; McAuley et al., 2006; von Schnehen et al., 2022). These tasks likely require greater cognitive resources, such as working memory and attention.

We reasoned that an SMS task with tempo changes, which is also more dependent on abilities like attention and cognitive control (Repp, 2001, 2005; Repp & Keller, 2004; Versaci & Laje, 2021), might similarly reveal age-related or NCD-related deficits in sensorimotor performance. However, our results did not support this hypothesis. Although we did observe a drop in performance following a tempo change in both studies, this decline was not significantly worsened by lower MMSE scores (**Chapter 4**) or age (**Chapter 5**). We analyzed performance by examining consistency and asynchrony per 15-second segments. The very large main effect of tempo stability in the current studies highlights the effectiveness of this manipulation in significantly reducing performance. However, we acknowledge that our analysis method may have not been sufficiently sensitive to uncover effects of healthy and/or pathological aging. Alternative measures, such as an adaptation index (Schwartze et al., 2011) or the length of a resynchronization period - the time taken for two tapping asynchronies to become statistically indistinguishable from baseline following a perturbation (Versaci & Laje, 2021) - might have been better adapted, given that people generally need much less than 15 seconds to adapt to a change in tempo. Additionally, with tempo changes, people's responses usually undergo a brief period of overcorrection, especially when the tempo changes are sufficiently large and consciously registered (Repp & Keller, 2004; Thaut et al., 1998). In a different neurological population, specifically patients with cerebellar lesions, it has been demonstrated that this overcorrection response is smaller than in healthy controls (Schwartze et al., 2016). Examining the dynamics of synchronization immediately following a perturbation may uncover effects of NCD that our current analysis did not capture

Future directions

An obvious next step would be to try to answer the question: Does rhythmic training confer cognitive benefits in aging and NCD? Given that SMS abilities vary as a function of cognitive functioning, training a person's rhythmic skill may lead to benefits in other domains, as has been proposed in Parkinson's disease, Huntington's Disease, autism, attention deficit hyperactivity disorder, and dyslexia (Allman et al., 2012; Bégel et al., 2022; Dalla Bella et al., 2017; Metzler-Baddeley et al., 2014; Noreika et al., 2013; Puyjarinet et al., 2017; Thomson et al., 2013). There is a need for randomized controlled trials in participants with NCD, to understand whether decline across multiple cognitive domains can be slowed as a result of rhythm-based interventions. The research of this PhD thesis underlines the importance of individual differences in the capacity to align movements with rhythmic sensory input, so music-based interventions should first identify an individual's rhythmic ability, adapt to it, and present gradually more complex stimuli to be at the same time accessible and to provide a certain level of challenge and stimulate one's SMS ability. Of course, healthy older adults are also a good target for music-based intervention. Recent interventional research has found improved cognitive abilities following piano training in healthy older adults (Marie et al., 2023). It would be interesting to examine whether similar results, or indeed even better results could be expected following an intervention that specifically focuses on training rhythmic skills. Specifically, our research suggests that training in sensorimotor skills may enhance inhibitory control.

A next step could be to supplement the current behavioral results with neuroimaging studies to further investigate the cognitive and neural mechanisms of SMS and their relationships with age and cognitive decline.

Electroencephalography and functional near-infrared spectroscopy might be particularly suitable, not only due to their temporal resolution but also for their relative non-invasiveness, which is important for research with NCD patients.

As detailed **Chapter 3**, one of the first stages of this research, which eventually led to this PhD thesis and its experiments, was the development of an experimental device designed for the assessment of SMS abilities and general engagement with music in older adults, including those with major NCD (Desmet et al., 2017; Lesaffre et al., 2017). This included, in the studies preceding this PhD (Ghilain, Hobeika, Lesaffre, et al., 2020; Ghilain, Hobeika, Schiaratura, et al., 2020; Hobeika et al., 2021) and in the first studies of this PhD (**Chapters 4 through 6**), the integration of a video recording of a musician performing the synchronization task in front of the participant (or, in some of the earlier studies, a real musician performing the task together with the patient). This approach was deemed necessary to create a less stressful and more motivating, engaging, and natural environment compared to the typical SMS situation, where participants sit in isolation and tap to a stimulus. Additionally, patients with NCD may experience difficulties in retaining and following instructions.

However, in the final study (**Chapter 7**), for the first time, we presented auditory stimuli without visual support. Although we made use of a large screen to show a video of a musician tapping along with the music for a practice trial, the screen remained blank for all experimental trials. Despite this change, the vast majority of participants succeeded at this task. Understanding the needs of patients with NCD in SMS research is crucial, and a future study could explore whether participants would still engage successfully without a video during the practice trial. More broadly, continued research is necessary to ensure that tasks commonly used to evaluate rhythm production and perception are suitable for geriatric populations. This is essential to avoid misinterpreting performance differences as motor deficits when they may actually be due to difficulties in understanding instructions, for example.

We encourage ongoing research that investigates tapping asynchrony in addition to consistency. Consistency, or its inverse, variability, is generally easily interpreted: Higher consistency equates to better performance and more successful synchronization. However, interpreting asynchrony is less straightforward. The observation that the negative mean asynchrony is reduced in musicians when synchronizing with a metronome (Aschersleben, 2002; Repp, 2004, 2010) and with music (**Chapter 5**), and that it is increased in people with cerebellar lesions (Schwartze et al., 2016), might suggest that 'optimal' performance corresponds to tapping exactly on the beat, with zero asynchrony.

Yet, if this is the case, it is surprising that younger individuals show more asynchrony than older individuals when tapping with music (**Chapter 5**) and that higher short-term memory performance is associated with earlier tapping (**Chapter 6**). Furthermore, in a previous study on the effects of audio type and social context on SMS, the same manipulations that yielded high consistency (i.e., tapping with a metronome in front of a video, as compared to with music and/or a live person) also resulted in lower negative asynchronies (Ghilain, Hobeika, Lesaffre, et al., 2020). While we hope to have contributed valuable data regarding SMS, phase locking, and its variability, more research is needed to fully understand their interplay.

In our review in **Chapter 2**, we discussed the diversity of cognitive profiles among people with NCD. Yet, our studies mostly included participants with mixed-origin NCD, Alzheimer's disease, and some with vascular NCD, which did not allow us to compare sensorimotor performance across different NCD etiologies. The sample sizes of specific conditions like NCD with Lewy bodies or frontotemporal NCD were too small for meaningful analysis. Thus, the goal of investigating SMS performance per NCD subtype remains.

A limitation of some of our research, and a direction for future studies, is the lack of standardized norms for several of our tests. For example, for the Gold-MSI, we only used a subset of items from the original battery, and it was not the same subset between the studies in **Chapters 5 and 7**. Similarly, we adapted the well-validated Go/No-go test from the Frontal Assessment Battery at Bedside (Dubois et al., 2000) but employed our own scoring method. Consequently, while we were able to use these variables to predict performance on sensorimotor tasks and identify relationships between musical expertise, cognitive abilities, and rhythmic abilities, we cannot determine, for example, if the sample in **Chapter 7** was generally very impaired in inhibition or not, or whether participants in **Chapters 5 and 7** had relatively high or low musical experience compared to other studies and samples.

Another interesting avenue for future research is how people, particularly older adults and those with NCD, move in synchrony with each other. Interpersonal SMS is influenced by various factors, including auditory temporal prediction ability, empathy, and perspective-taking (Fairhurst et al., 2013; Novembre et al., 2019; Pecenka & Keller, 2011; Rosso et al., 2023; Washburn et al., 2021). It would be interesting to investigate how NCD, which can manifest as impairments in social cognition (Bediou et al., 2009; Shany-Ur & Rankin, 2011), affects interpersonal SMS. Understanding this relationship could significantly enhance the development of music-based interventions, which often depend on musical interactions between the therapist and patient, or between patients (Hobeika & Samson, 2020; Sherratt et al., 2004).

Music has a unique power to bring people together and make them move, synchronizing them to its beat and with each other. To understand how best to use this potential in rehabilitative settings for older adults, this PhD project sought out how aging and NCD impact SMS. Although older adults and individuals with NCD certainly continue to be sensitive to and moved by music, their ability to move it may depend on the preservation of certain cognitive abilities, particularly inhibition and short-term memory. This dependency is especially pronounced when the rhythm is complex and the beat is not easily discernible. However, these findings also suggest that enhancing rhythmic abilities could stimulate cognitive functions. I am confident that we will soon see research that delves into this causal relationship, leading to exciting interventional studies to improve the lives of our seniors.

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