Aging Brain 3 (2023) 100076

Contents lists available at ScienceDirect

Aging Brain

journal homepage: www.elsevier.com/locate/nbas

Longitudinal grip strength is associated with susceptibility to the Sound Induced Flash Illusion in older adults

A. O' Dowd [a,b,*], R.J. Hirst [a,b], A. Setti [b,c], R.A. Kenny [b,d], F.N. Newell [a]

[a] School of Psychology and Institute of Neuroscience, Trinity College Dublin, Ireland
[b] The Irish Longitudinal Study on Ageing, Trinity College Dublin, Ireland
[c] School of Applied Psychology, University College Cork, Ireland
[d] Mercer Institute for Successful Ageing, St James. Hospital, Dublin, Ireland

A R T I C L E I N F O

Article history:
Received 19 January 2023
Revised 20 April 2023
Accepted 3 May 2023

Keywords:
Ageing
Grip strength
Multisensory
Sound Induced Flash Illusion

A B S T R A C T

The precision of temporal multisensory integration is associated with specific aspects of physical functioning in ageing, including gait speed and incidents of falling. However, it is unknown if such an association exists between multisensory integration and grip strength, an important index of frailty and brain health and predictor of disease and mortality in older adults. Here, we investigated whether temporal multisensory integration is associated with longitudinal (eight-year) grip strength trajectories in a large sample of 2,061 older adults (mean age = 64.42 years, *SD* = 7.20; 52% female) drawn from The Irish Longitudinal Study on Ageing (TILDA). Grip strength (kg) for the dominant hand was assessed with a hand-held dynamometer across four testing waves. Longitudinal k-means clustering was applied to these data separately for sex (male, female) and age group (50–64, 65–74, 75+ years). At wave 3, older adults participated in the Sound Induced Flash Illusion (SIFI), a measure of the precision of temporal audio-visual integration, which included three audio-visual stimulus onset asynchronies (SOAs): 70, 150 and 230 ms. Results showed that older adults with a relatively lower (i.e., weaker) grip strength were more susceptible to the SIFI at the longer SOAs compared to those with a relatively higher (i.e., stronger) grip strength (p <.001). These novel findings suggest that older adults with relatively weaker grip strength exhibit an expanded temporal binding window for audio-visual events, possibly reflecting a reduction in the integrity of the central nervous system.

Introduction

There is growing evidence that the precision by which the brain combines information across the senses, multisensory integration, is reduced in older adults. That is, while there is evidence that older adults can exhibit a larger benefit from multisensory relative to unisensory cues compared to their younger counterparts [1–3], sustained multisensory integration over longer temporal intervals is also evidenced in ageing [4–7]. This is interpreted as an age-related 'expansion' of the temporal binding window (TBW), the optimal period of time in which sensory inputs are integrated [8–10]. For example, in the Sound Induced Flash Illusion, SIFI [11,12], a measure of temporal audio-visual integration in which the presentation of one 'flash' alongside two 'beeps' typically results in the perception of two 'flashes', older adults routinely report perceiving the additional illusory flash across longer audio-visual offsets than young adults [4–7,13]. Moreover, illusion

* Corresponding author at: School of Psychology and Institute of Neuroscience, Trinity College Dublin, Dublin, Ireland.

E-mail address: odowda1@tcd.ie (A. O' Dowd).

https://doi.org/10.1016/j.nbas.2023.100076
2589-9589/

susceptibility at longer temporal delays continues to increase in older age [4].

Less precise temporal multisensory integration is particularly pronounced in older adults who exhibit reduced cognitive function [4,14,15], across multiple subdomains of cognition [15], indicating a relationship between multisensory integration and global brain health. In addition, older adults with relatively slow gait speed [16] or who report incidents of falling [7,17] demonstrate increased susceptibility to the SIFI at longer temporal offsets, when controlling for global cognitive function. Collectively, these findings indicate that the temporal precision of multisensory integration is interlinked with the broader cognitive and physical health of an older adult, thereby emphasising the value of investigating multisensory perception in ageing. These findings are perhaps unsurprising, as multisensory integration is considered an important 'scaffold' for higher-order cognition [18] and normal motor functions [19]; for example, holding a conversation or walking both have integral multisensory and temporal components [18,19].

Grip strength is a critical index of physical functioning, frequently utilised in clinical settings as a straightforward way to gauge overall body strength and to discriminate the functional capacity and potential frailty of an older adult [20–23]. Grip strength is associated with a higher number of markers of frailty than chronological age in both males and females [23] and is a significant predictor of functional decline and disability [24,25], disease [26,27], mortality [27,28], fall incidents [22] and brain health [29–31]. Moreover, grip strength has been associated with self-reported impaired vision and hearing as well as reduced visual acuity and poorer eye health in older adults [32,33], suggesting an association between physical strength and sensory function in ageing. Collectively, these findings perhaps indicate common mechanisms underlying age-related declines across several domains of functioning [33–36]. However, no study has investigated if the precision of multisensory integration is associated with grip strength in older adults. Exploring this relationship is important given that multisensory integration is critical to everyday functioning [18,19] and is a potential index of healthy versus less healthy ageing [4,7,14–17]. Moreover, this would help to determine if patterns of temporal multisensory integration in older adults are sensitive to multiple indices of potential frailty or if such associations maintain only for specific aspects of functional mobility, such as the speed and flexibility of an older adult's gait [16] which is more obviously reliant on multisensory integration [18]. As such, we examined whether grip strength performance was associated with susceptibility to the SIFI in a large sample of community-dwelling older adults drawn from The Irish Longitudinal Study on Ageing (TILDA [37]). We focused on longitudinal as opposed to cross-sectional patterns of grip strength as the former allowed for a more comprehensive profile of the physical strength of these older adults over an extended (eight-year, spanning four testing waves) period. Based on previous findings from this sample linking less precise multisensory integration with reduced cognitive or physical health [4,15–17], we hypothesised that those with reduced grip strength over time would be more susceptible to the SIFI at longer audio-visual asynchronies compared to their stronger counterparts.

Methods

Study population

Participants were drawn from waves 1 – 4 (2009 – 2016) of TILDA, a population representative sample of 8,504 individuals, resident in the Republic of Ireland [37]. The study was approved by the Trinity College Dublin Faculty of Health Sciences Research Ethics Committee and complied with relevant data protection legislation. All participants provided informed consent at every testing wave. In total, 4,771 older adults had available data for all four waves and, of these, 3,654 had data available for the Sound Induced Flash Illusion (SIFI) experiment conducted only at wave 3. Consistent with previous studies involving the TILDA cohort, in which SIFI susceptibility was the outcome measure [4,15–17], data were omitted prior to analysis for participants who met the following criteria: younger than 50 years at wave 1 (n = 189), were registered as legally blind at wave 3, when SIFI was conducted (n = 2), had a suspected mild cognitive impairment at wave 3 (based on a Montreal Cognitive Assessment Score < 23; n = 387) and/or had missing/problematic data for important model predictors/covariates (n = 1,015, 757 of whom were missing grip strength data for all four waves and nineteen of whom self-reported levels of physical activity of ≥ 16hrs/-day). This resulted a final sample of 2,061 older adults (mean age = 64.42 years, *SD* = 7.20; 52% female) whose data were available for analysis.

Grip strength

At all four waves, older adults provided a measure of their grip strength. This was conducted in a healthcare setting as part of a comprehensive health assessment at waves 1 and 3 and in the participant's home environment at waves 2 and 4. All assessments of grip strength, measured in kilograms, were performed in the presence of a trained interviewer. Participants were asked to squeeze a hydraulic hand dynamometer (Baseline, Fabrication Enterprises, Inc, White Plains, NY) as hard as possible for a few seconds. While the same testing protocols were used in the healthcare and home settings, four readings were taken during the former (two on the dominant hand and two on the non-dominant hand) and two readings were taken during the latter (two on the dominant hand only). Therefore, the average reading for grip strength on the dominant hand was extracted at each wave for our analysis. As our aim was to investigate the association between long-term grip strength profiles and multisensory integration, we applied longitudinal k-means clustering via the 'kml' package [38] in R to these grip strength data, which were continuous in nature. As expected, there was a sex difference in grip strength, in which males had, on average, a higher grip strength compared to females across all four waves (see Fig. 2 and Supplementary Materials, Table S1).

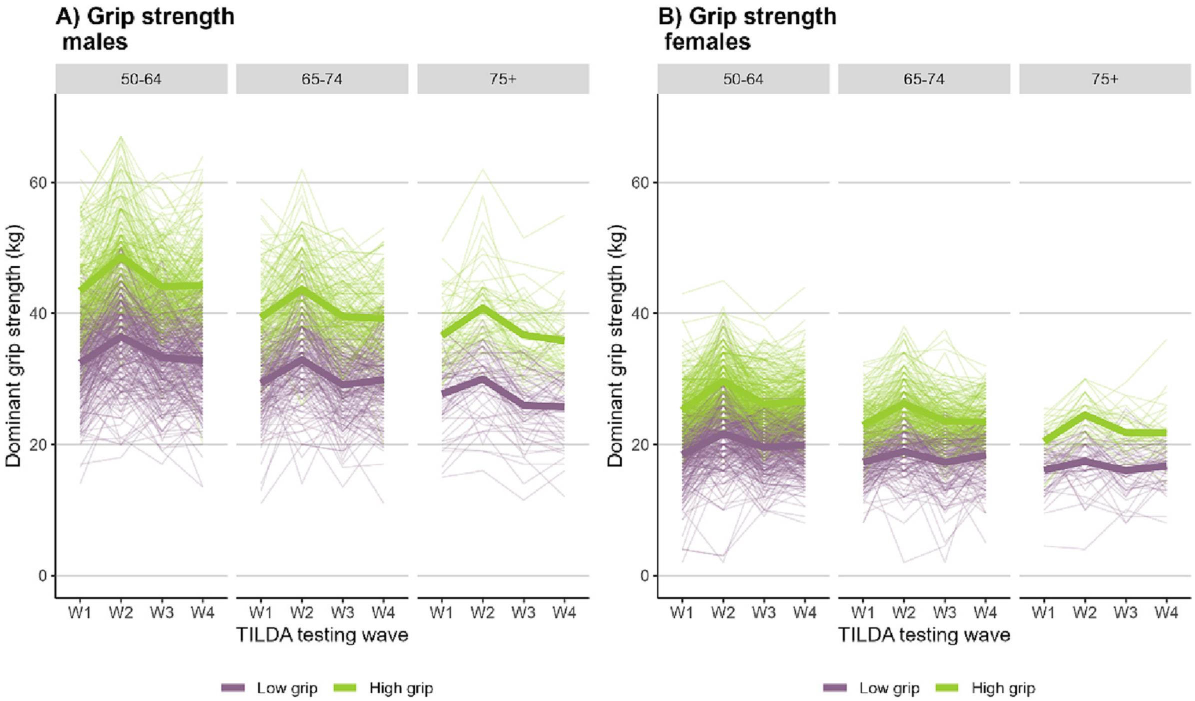

Fig. 1. Plots show the groups for average grip strength on the dominant hand (kg) for (a) males across age groups and (b) females across age groups. Thick lines indicate the mean trajectory over the four waves (W1 – W4) and thin lines indicate individual grip strength trajectories. Sample sizes are as follows: **High dominant grip strength:** Males 50–64 years = 227; Males 65–74 years = 160; Males 75 + years = 58; Females 50–64 years = 300; Females 65–74 years = 208; Females 75 + years = 35. **Low dominant grip strength:** Males 50–64 years = 300; Males 65–74 years = 187; Males 75 + years = 66; Females 50–64 years = 304; Females 65–74 years = 160; Females 75 + years = 56.

There was also an expected age difference, in which grip strength declined with increasing age (see Fig. 2 and Supplementary Materials, Table S1). Therefore, k-means clustering was applied separately for males and females and, within each sex group, separately for three distinct age groups (50–64, 65–74 and 75 + years, with the selection of these age groups based on previous research involving the TILDA sample; e.g., [4,39]).

Performance on the Sound-Induced Flash Illusion

The precision of temporal multisensory integration was assessed as susceptibility to the Sound Induced Flash Illusion (SIFI [11,12]) across three Stimulus Onset Asynchronies (SOAs) of varying duration. SIFI susceptibility measures the temporal precision of audio-visual integration and is associated with activity in the primary visual and auditory cortices [13,40,41] as well as the superior temporal sulcus, angular gyrus and anterior cingulate [13,42–44]. The SIFI was included as part of a comprehensive health assessment only at wave 3 of TILDA. The task was performed in the presence of a trained healthcare nurse. Participants were seated approximately 60 cm from a computer (Dell Latitude E6400 with Intel Core 2 Duo CPU, 2 Gb RAM, using Windows 7 Professional OS, 60 Hz refresh rate) and fixated on a fixation cross (1,000 ms) located at the centre of the screen. On each trial, a visual stimulus (a white disc, 1.5° visual angle, approximately 32 fl luminance) and/or auditory (brief bursts 3500 Hz sounds (10 ms, 1 ms ramp)) stimuli were presented. The visual stimulus was presented on a black background (5 cm beneath the central fixation cross, approximately 4.7° visual angle), for 16 ms. The auditory stimuli were presented at approximately 80 dB over the computer speakers.

The main testing block contained a random order of multisensory illusory trials (2B1F, in which 2 Beeps are paired with one Flash), non-illusory trials (2B2F, 1B1F) and unisensory visual trials (0B2F, 0B1F), each presented twice. The participants reported the number of perceived visual flashes. Unisensory auditory trials (1B0F, 2B0F) were presented in a separate block and participants reported the number of perceived auditory beeps. Participants' vocal responses were recorded by the nurse who pressed the corresponding number key on a laptop. Illusion trials of the SIFI consisted of three SOAs, 70 ms, 150 ms and 230 ms, and the second beep either preceded (pre) or followed (post) the flash-beep pair. Due to time constraints within the overall TILDA protocol, a total of twelve 'illusory' trials were completed (i.e., two trials per SOA across pre-post conditions). Overall, the experiment was completed in approximately six minutes.

Analysis

Response accuracy to illusion trials (2 beeps with 1 flash) of the SIFI task constituted the main outcome of this study. An accurate response indicated that the participant

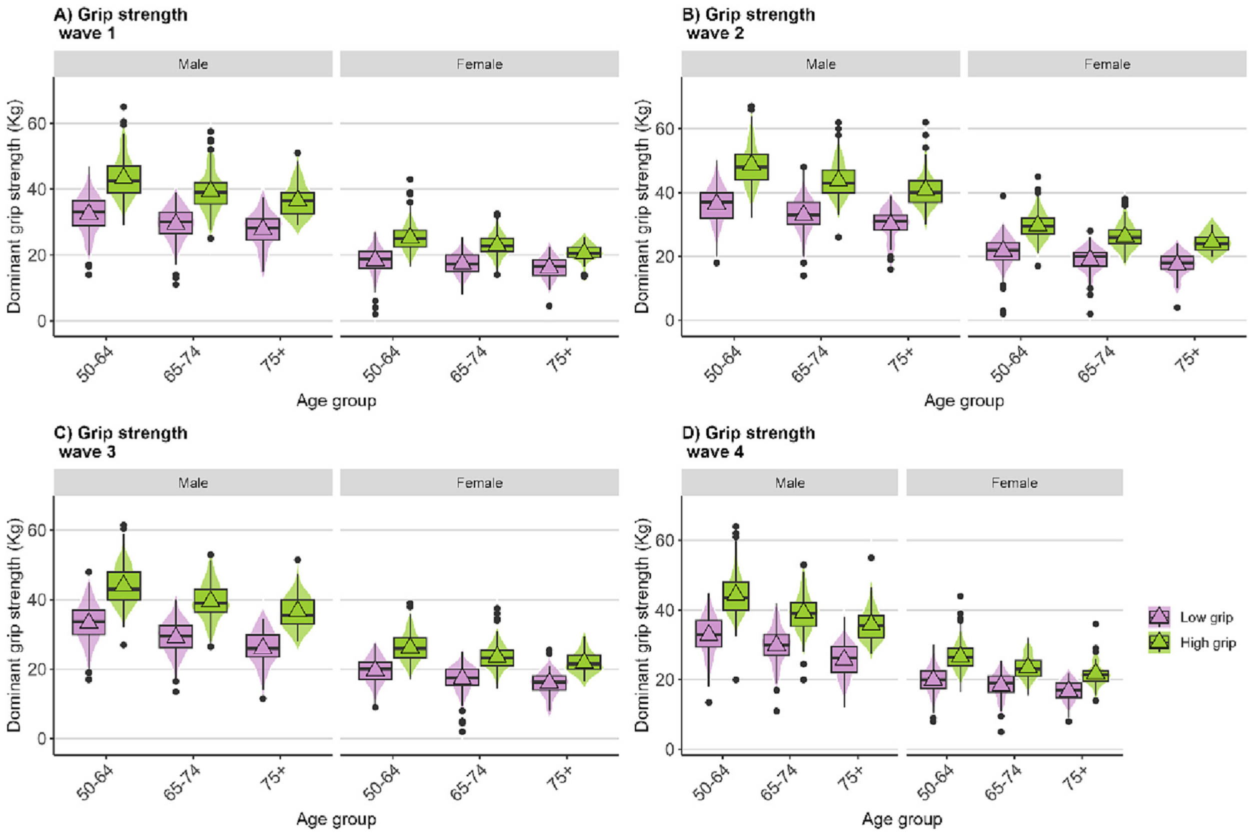

Fig. 2. Plot shows dominant grip strength values for the high and low longitudinal grip strength groups across age groups and participant sex, separately for waves 1 – 4 (panels A – D). Mean values are illustrated with large triangle points. Boxplot and violin plots show the distribution of grip strength values per longitudinal grip strength group. Small circles show outliers.

was not susceptible to the illusion on that trial. As there were two trials per condition of the SIFI within TILDA, accuracy took the form of 0 (i.e., an incorrect response on both trials, indicating illusion susceptibility), 0.5 (correct response on one trial) or 1 (correct response on both trials) and was treated as a discrete variable. Generalised logistic mixed effects regression models were fitted to these data via the 'lme4' package [45].

All statistical models controlled for a range of covariates, as in previous studies involving the TILDA sample [4,15–17]. The following terms were included in the model: age, stimulus onset asynchrony (SOA; 70, 150, 230 ms), longitudinal grip strength group (GSGroup), sex (male, female), education (primary, secondary, tertiary), self-reported vision and audition (poor to excellent), visual acuity score (VAS = 100 – 50 * LogMAR), hearing aid use (yes, no), number of cardiac (0, 1, 2+) and non-cardiac (0, 1, 2+) diseases, depression (CES-D $\geq$ 9), body mass index (BMI; kg/m^2), weekly physical activity (metabolic minutes a week based on the International Physical Activity Questionnaire), accuracy (0, 0.5, 1) on multisensory congruent (1 beep and 1 flash), unimodal visual (2 flashes only; 70 ms SOA) and unimodal auditory trials (2 beeps only; 70 ms SOA) and pre-post condition. To ensure that any significant interaction between SOA and grip strength was not explained by differences in cognition or gait speed between the two longitudinal grip strength groups at wave 3, when the SIFI was completed (see Supplementary Materials, Table S2), the models were also adjusted for MoCA score and a measure of gait speed flexibility (delta maximal gait speed: maximal gait speed - usual gait speed/ usual gait speed; as in [16]), both of which are independently associated with increased susceptibility to the illusion at longer SOAs [4,16]. The analysis model also included SOA*age, SOA*sex, SOA*MoCA, SOA*gait and SOA*pre-post interaction terms and a random intercept term (participant ID). To address our hypothesis that maximum grip strength would be associated with the precision of temporal multisensory integration in older adults, we examined whether the effect of SOA on accuracy, using the 70 ms as the reference condition, interacted with longitudinal grip strength group (SOA*GSgroup). The statistical significance of the SOA*GSGroup interaction term was determined by a likelihood ratio test, where we assessed the fit of the model with and without this interaction term while holding constant all the aforementioned covariates.

The analysis was conducted with R in R studio [46]. Supplementary materials (full model results and R script) are available at https://osf.io/n3hdq/?view_only=6788dd4a4b774d11b9cffdd533b1b29c. All continuous variables were scaled prior to analysis.

Results

Grip strength trajectories

Longitudinal k-means clustering, applied to the longitudinal grip strength data with 1 – 5 clusters and 100 redraws, produced optimal solutions of two groups for dominant grip strength for both older adult males and females across age groups. These solutions were identified as optimal with visual inspection of Caliński-Harabasz [47] criterion plots (see Supplementary Materials), a well-established method of determining the optimal clustering solution (see Supplementary Materials). The final clustering solutions are shown in Fig. 1[a].

Between-groups *t*-tests confirmed that, at every testing wave, the high and low longitudinal grip strength groups differed significantly on their average dominant grip strength across all age groups, for both males and females, when considering the Bonferroni-adjusted alpha level of α = 0.002, as shown in Fig. 2 (see also Supplementary Materials, Table S1). These results verified that the two-group solution reflected genuinely distinct longitudinal grip strength profiles for these older adults. As such, we pooled together these clusters into a single representation of longitudinal grip strength trajectories for the entire sample, consisting of 'high' (n = 988) versus 'low' (n = 1,073) grip strength. Importantly, as a result of our clustering approach, older adults were characterised as having high or low grip strength only relative to older adults of the same sex and age group. Descriptive statistics for these two groups at wave 3, when the older adults participated in the SIFI, are available in Supplementary Materials (Table S2) and further confirm that those in the low longitudinal grip strength group had reduced functional capacity more broadly relative to those in the high longitudinal grip strength group.

Multisensory integration (SIFI performance)

The likelihood ratio test revealed that the SOA*GSGroup term significantly contributed to the model predicting accuracy on illusion trials of the SIFI ($\chi^2_{(2)}$ = 28.05, p <.001) as shown in Fig. 3A. This interaction was driven by increased SIFI susceptibility at the 150 ms and 230 ms SOAs relative to the 70 ms SOA for those in the low GSGroup compared to those in the high GSGroup, as shown in Fig. 3B. More specifically, older adults with a low GS exhibited 33% and 35% lower odds of making an accurate response at 150 ms (odds ratio = 0.67, 95% CI [0.56,0.80]) and 230 ms (odds ratio = 0.65, 95% CI [0.54,0.78]), relative to 70 ms respectively, compared to older adults with a high GS. As shown in Fig. 3B and Table 1, the difference in the predicted accuracy values (marginal means) for responses on the illusion trials of the SIFI were 28% versus 34% for the high and low GS groups respectively at 150 ms (versus 70 ms) and 28% versus 34% for the high and low GS groups respectively at 230 ms (versus 70 ms). Full model results are available in Supplementary Materials, Table S3.

Discussion

We investigated the association between longitudinal (eight-year) trajectories of average grip strength in the dominant hand and multisensory integration, measured via susceptibility to the Sound Induced Flash Illusion (SIFI [11,12]), among a large sample of community-dwelling older adults (N = 2,061). Older adults were classified into high and low longitudinal grip strength groups relative to those of the same sex and age group using longitudinal k-means clustering [38]. Our results showed that older adults with a high dominant grip strength were less susceptible to the SIFI at longer audio-visual offsets (versus the shortest offset) relative to those with a low dominant grip strength. Importantly, the effect of longitudinal grip strength group alone on SIFI susceptibility was not statistically significant. This is consistent with other findings from the TILDA sample and other empirical ageing studies involving the SIFI, namely that the associations between audio-visual integration and factors such as age [4–7], cognitive function [4,15], gait speed [16] and incidents of falls [7,17], are shaped by the manipulation of the audio-visual stimulus onset asynchrony (SOA). As such, older adults with higher grip strength for the dominant hand (relative to their own age and sex group, as measured over four waves, i.e., over eight years) show higher levels of temporal precision in audio-visual integration (i.e., are less susceptible to the SIFI at longer SOAs) compared to older adults with lower dominant hand grip strength.

The significant interaction between grip strength and SOA is consistent with a wider audio-visual temporal binding window (TBW) in physically less healthy older adults. The audio-visual TBW is the period of time in which audio-visual inputs are most likely to be integrated [8–10] and it typically expands during the healthy ageing process [4–7,13]. While a wider TBW may be a compensatory mechanism for age-related declines in unisensory abilities [6,48], it is also potentially maladaptive and a marker of less healthy functioning. Indeed, our results align well with previous findings from the TILDA sample and others that sustained integration over longer audio-visual offsets is pronounced in older adults with reduced cognitive function [4,14,15], restricted mobility [16] or those who are fall-prone [7,17]. In other words, the temporal precision of multisensory integration has the capacity to discriminate older adults based on multiple facets of cognitive or physical health. Achieving a greater understanding of the relationship between the physical and perceptual functioning of an older adult is particularly important in light of evidence that these dimensions are independently associated with preventable outcomes such as incidents of falling and frailty [7,17,20–22]. The present findings, together

[a] We acknowledge that there was a moderate increase in the average dominant grip strength at wave 2 compared to the other testing waves. Notably, the same testing protocol was used at all waves, there were no recorded issues with the grip strength measurements at any of the four waves and grip strength was assessed in the home environment at both waves 2 and 4. The cause of this increase in recorded grip strength at wave 2 has not been identified. However, as all groups showed the same pattern at wave 2, therefore this was not considered problematic for group comparisons.

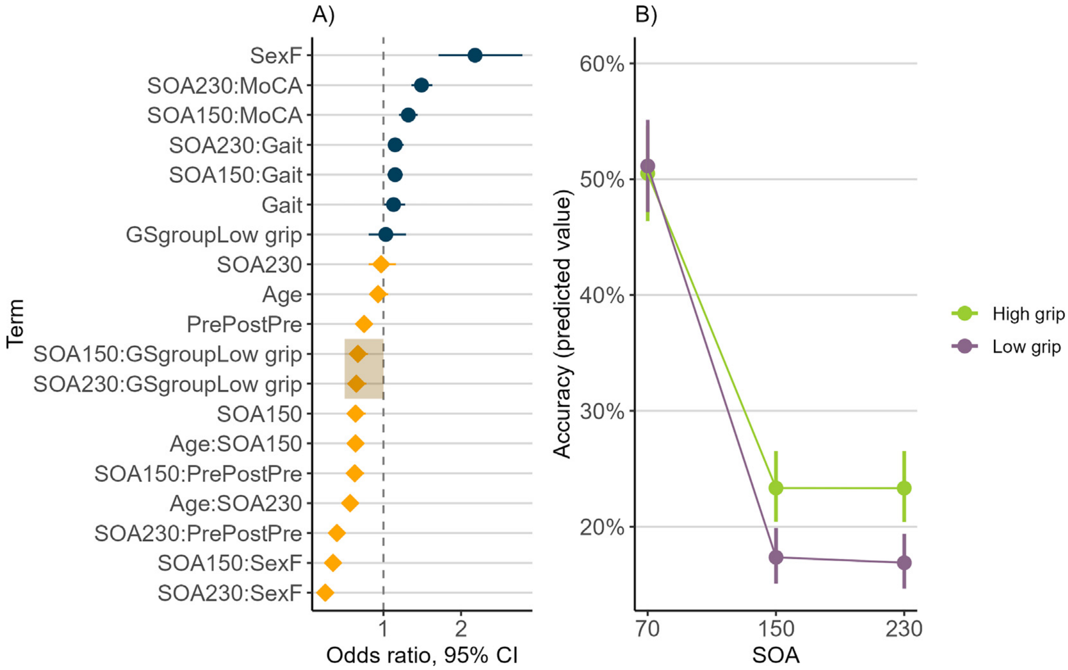

Fig. 3. Summary of the results of generalised logistic mixed-effects regression models predicting accuracy on 2B1F trials of the SIFI. (A) Plot shows the odds ratios (with 95% confidence intervals) for key terms from generalised logistic mixed-effects regression models predicting accuracy on illusion (2B1F) trials of the SIFI. Odds ratios to the left of the vertical dashed line (yellow diamonds) indicate reduced odds of making a correct response (i.e., increased illusion susceptibility) and odds ratios to the right of the vertical dashed line (blue circles) indicate increased odds of making a correct response (i.e., reduced illusion susceptibility). The odds ratios for the statistically significant interaction between SOA and longitudinal grip strength group (GSgroup) are highlighted. B) The predicted accuracy values (marginal means) for responses on illusion (2B1F) trials of the SIFI across longitudinal grip strength groups. Higher values indicate increasingly correct identification the number of flashes presented (whilst ignoring the beeps), therefore reduced susceptibility to the illusion. Error bars indicate 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Table shows the predicted values [marginal means; 95% confidence intervals] of making an accurate response across stimulus onset asynchronies (SOA; 70, 150, 230 ms) for the high and low longitudinal grip strength groups.

	70 ms	150 ms	230 ms	70 v 150	70 v 230
High grip (*n* = 988)	51% [46,55]	23% [20,27]	23% [20,27]	28%	28%
Low grip (*n* = 1,073)	51% [47,55]	17% [15,20]	17% [15,19]	34%	34%

with those of Setti et al. [16], demonstrate that an accessible, cost-effective and easy-to-administer measure of temporal audio-visual integration is sensitive to at least two well-recognised, fundamental dimensions of physical frailty: gait speed and grip strength [20,21]. Therefore, we propose that the precision by which the brain combines sensory information in time is a critical aspect of the ageing process, meriting greater attention in empirical studies of ageing and in assessments of the functional capacity of an older adult.

Perhaps the most parsimonious explanation for the current findings is that older adults with lower grip strength have relatively less healthy functioning of the central nervous system (CNS) compared to their stronger counterparts. This would be expected to not only adversely impact on their capacity to apply sufficient grip force but also the efficiency with which they can integrate sensory signals in time [49,50]. Indeed, grip strength specifically has been described as a vital sign and 'indispensable biomarker' of health [22,24,31], with enormous value as a single, non-invasive measure of an older adult's risk of future functional decline [22,24,31]. The capacity for grip strength performance to provide broad insight into the integrity of the CNS has been highlighted [31] and several lines of evidence support this [31]. To begin with, the recruitment of central mechanisms for motor control is reported to be enhanced in older adults, possibly to compensate for concomitant declines in the peripheral nervous system [51–53]. Reduced grip strength performance in older adults is also linked with variations in both the structural and functional characteristics of the brain [54,55]. In addition, application of grip force is altered during healthy ageing, in a manner consistent with a decreased ability to coordinate motor commands via CNS mechanisms [31]. Finally, grip strength is associated with a range of higher-order cognitive abilities, including processing speed and verbal fluency, and can be predictive of cognitive decline and cognitive impairment in ageing [29–31,56–58].

The latter finding may indicate shared neural substrates for motor and higher-order cognitive functions [31]. Indeed, activity in motor regions of the brain, such as the supplementary motor area (SMA) which is active during the application of grip force [59,60], is observed during tasks of numerical cognition [31,61] or temporal discrimination in the absence of any explicit motor demands [62]. Furthermore, frail individuals (without global cognitive impairment) show altered patterns of oscillatory activity within and functional connectivity between multiple fronto-parietal regions, including the right angular gyrus (rAG) [63,64]. The angular gyrus is considered an important nexus for different subsystems of the brain [65]. Disruption of the rAG via transcranial magnetic stimulation (TMS) reduces the occurrence of the SIFI in young adults [43,44] while variations in grey matter volume in the rAG in older adults in the TILDA sample is associated with differences in susceptibility to the SIFI at longer SOAs [42]. However, it is important to note that relatively few older adults in the TILDA sample qualify as 'frail' per se, at least based on the criteria of the Fried frailty phenotype [20,21].

In line with the proposed links between grip strength and the broader integrity of the CNS, exploratory analyses of other health variables at wave 3, when the older adults participated in the SIFI, confirmed that those with a low grip strength were considerably less healthy than their stronger counterparts on numerous dimensions (see Supplemental Materials, Table S2). For example, compared to the latter group, older adults with reduced grip strength exhibited lower scores on the Montreal Cognitive Assessment (MoCA) and slower processing speed (measured with the Choice Response Time task) as well as poorer immediate and delayed recall (of verbally presented words) and verbal fluency (timed animal naming). They also presented with slower gait speed and slower sit-to-stand times, worse visual acuity and a higher percentage of self-reported fair/poor vision than those with a high grip strength. Collectively, these findings are consistent with evidence linking weaker grip strength with reduced mobility [22,66,67] and cognition [29–31,56–58] as well as less healthy visual functioning [32,33], supporting our hypothesis that differences in multisensory integration based on grip strength likely reflect differences in CNS functioning (i.e., brain health) in ageing. Importantly, the present results emerged while controlling for these effects at wave 3 in our analysis, indicating that the relationship between grip strength and multisensory integration cannot be fully accounted for by these factors. However, we acknowledge that many of these group differences were relatively small (see Supplementary Materials, Table S1), as was the group difference in the predicted accuracy values for responses at the long versus short SOAs of the SIFI (6% for both 150 and 230 ms versus 70 ms). This likely reflects that, overall, the older adults in the TILDA study are relatively young and high-functioning, limiting the extent to which performance on these various measures diverged between the two groups.

To account for links between sensorimotor and cognitive abilities in ageing, some have proposed a 'common cause' hypothesis, namely that a common, biological mechanism(s) (e.g., white matter integrity) underpins concomitant age-related changes in performance across multiple domains of functioning [34–36,53]. Reduced availability and increased interdependency of neural resources in ageing, leading to a compensatory trade-off across domains, may also play a role [35]. However, a common cause model is not consistently supported by empirical evidence to fully explain these relationships [36,68,69] and given their appreciable complexity, the specific mechanisms involved remain unclear. This is true for the data presented here as, at the present time, we cannot interpret directionality or causality in our findings, given that the SIFI was administered once, at wave 3 only of the TILDA study, and the longitudinal trajectories of grip strength incorporated data from the preceding and following waves. In addition, susceptibility to the SIFI can be determined by various factors, including the weighting of sensory inputs based on their relative reliability [48,49] and the degree of prior expectation of audio-visual numerical compatibility [70]. Further empirical work will be needed to establish exactly which processes (bottom-up, top-down or both) are impacted in less healthy older adults, contributing to their wider TBW. We also acknowledge that there are limitations in the number of trials and range of SOAs in the current SIFI paradigm, limiting our ability to precisely map the TBW in these older adults. This is important to clarify, as ageing can influence several morphological characteristics of the TBW, including its peak height and width [6], but the TBW can also be positively shaped by perceptual training [6]. These limitations can be readily addressed in follow-up empirical research.

Conclusions

We investigated whether the temporal precision of multisensory integration was associated with longitudinal (eight-year) trajectories of average grip strength in the dominant hand, using data from a large sample of community-dwelling older adults (N = 2,061) drawn from The Irish Longitudinal Study on Ageing (TILDA). Reduced susceptibility to the audio-visual Sound Induced Flash Illusion [11,12] at longer audio-visual delays was observed in older adults with stronger grip strength compared to their physically weaker counterparts, suggesting that grip strength performance is associated with the width of the audio-visual temporal binding window, perhaps reflecting reduced integrity of the central nervous system. These findings provide novel evidence that an accessible measure of audio-visual integration is sensitive to performance on a key indicator of physical functioning and brain health in ageing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Health Research Board [Grant reference ILP-PHR-2017-014]. The funder had no role in the study, analysis or manuscript preparation.

Author contributions

The Irish Longitudinal Study on Ageing (TILDA) is co-ordinated by R.A.K. A.S. and F.N.N. designed the protocol for the Sound-Induced Flash Illusion incorporated into TILDA at wave 3. All authors substantially contributed to the conception and planning of the work or the acquisition, analysis and interpretation of the data. All authors substantially contributed to the theoretical interpretation of the results. A.O'D drafted the manuscript. All authors provided feedback and revisions on the manuscript for important intellectual content. All authors approved the final version of the manuscript for submission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nbas.2023.100076.

References

[1] De Dieuleveult AL, Siemonsma PC, Van Erp JB, Brouwer AM. Effects of aging in multisensory integration: a systematic review. Front Aging Neurosci 2017:80. doi: https://doi.org/10.3389/fnagi.2017.00080.
[2] Laurienti PJ, Burdette JH, Maldjian JA, Wallace MT. Enhanced multisensory integration in older adults. Neurobiol Aging 2006;27:1155–63. doi: https://doi.org/10.1016/j.neurobiolaging.2005.05.024.
[3] Jones SA, Noppeney U. Ageing and multisensory integration: a review of the evidence, and a computational perspective. Cortex 2021;138:1–23. doi: https://doi.org/10.1016/j.cortex.2021.02.001.
[4] Hernández B, Setti A, Kenny RA, Newell FN. Individual differences in ageing, cognitive status, and sex on susceptibility to the sound-induced flash illusion: a large-scale study. Psychol Aging 2019;34:978. doi: https://doi.org/10.1037/pag0000396.
[5] McGovern DP, Roudaia E, Stapleton J, McGinnity TM, Newell FN. The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration. Front Aging Neurosci 2014;6:250. doi: https://doi.org/10.3389/fnagi.2014.00250.
[6] McGovern DP, Burns S, Hirst RJ, Newell FN. Perceptual training narrows the temporal binding window of audiovisual integration in both younger and older adults. Neuropsychologia 2022;173:. doi: https://doi.org/10.1016/j.neuropsychologia.2022.108309108309.
[7] Setti A, Burke KE, Kenny RA, Newell FN. Is inefficient multisensory processing associated with falls in older people? Exp Brain Res 2011;209:375–84. doi: https://doi.org/10.1007/s00221-011-2560-z.
[8] Wallace MT, Stevenson RA. The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. Neuropsychologia 2014;64:105–23. doi: https://doi.org/10.1016/j.neuropsychologia.2014.08.005.
[9] Diederich A, Colonius H. The time window of multisensory integration: relating reaction times and judgments of temporal order. Psychol Rev 2015;122:232. doi: https://doi.org/10.1037/a0038696.
[10] Meredith MA, Nemitz JW, Stein BE. Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. J Neurosci 1987;7:3215–29. doi: https://doi.org/10.1523/JNEUROSCI.07-10-03215.1987.
[11] Shams L, Kamitani Y, Shimojo S. What you see is what you hear 788-788. Nature 2000;408. doi: https://doi.org/10.1038/35048669.
[12] Shams L, Kamitani Y, Shimojo S. Visual illusion induced by sound. Cog Brain Res 2002;14:147–52. doi: https://doi.org/10.1016/S0926-6410(02)00069-1.
[13] Hirst RJ, McGovern DP, Setti A, Shams L, Newell FN. What you see is what you hear: twenty years of research using the Sound-Induced Flash Illusion. Neurosci Biobehav Rev 2020;118:759–74. doi: https://doi.org/10.1016/j.neubiorev.2020.09.006.
[14] S Chan J, Kaiser J, Brandl M, Matura S, Prvulovic D, J Hogan M, J Naumer M. Expanded temporal binding windows in people with mild cognitive impairment. Curr Alzheimer Res 2015;2015(12):61–8. doi: https://doi.org/10.2174/1567205012666141218124744.
[15] Hirst RJ, Setti A, De Looze C, Kenny RA, Newell FN. Multisensory integration precision is associated with better cognitive performance over time in older adults: a large-scale exploratory study. Aging Brain 2022;2:. doi: https://doi.org/10.1016/j.nbas.2022.100038100038.
[16] Setti A, Hernández B, Hirst RJ, Donoghue OA, Kenny RA, Newell FN. Susceptibility to the sound-induced flash illusion is associated with gait speed in a large sample of middle-aged and older adults 112113–112113. Exp Gerontol 2023. doi: https://doi.org/10.1016/j.exger.2023.112113.
[17] O Dowd A, Hirst RJ, Donoghue OA, Kenny RA, Newell FN. The temporal precision of audiovisual integration is associated with longitudinal fall incidents but not sensorimotor fall risk in older adults. Sci Rep 2023; 13: 7167. https://doi.org/10.1038/s41598-023-32404-y
[18] Wallace MT, Woynaroski TG, Stevenson RA. Multisensory integration as a window into orderly and disrupted cognition and communication. Ann Rev Psychol 2020;71:193–219. doi: https://doi.org/10.1146/annurev-psych-010419-051112.
[19] Paraskevoudi N, Balcı F, Vatakis A. "Walking" through the sensory, cognitive, and temporal degradations of healthy aging. Ann New York Acad Sci 2018;1426:72–92. doi: https://doi.org/10.1111/nyas.13734.
[20] Fried LP, Tangen CM, Walston J, Newman AB, Hirsch C, Gottdiener J, et al. Frailty in older adults: evidence for a phenotype. J Gerontol A: Biol Sci Med Sci 2001;56:146–57. doi: https://doi.org/10.1093/gerona/56.3.M146.
[21] Savva GM, Donoghue OA, Horgan F, O'Regan C, Cronin H, Kenny RA. Using timed up-and-go to identify frail members of the older population. J Gerontol A: Biol Sci Med Sci 2013;68:441–6. doi: https://doi.org/10.1093/gerona/gls190.
[22] Bohannon RW. Grip strength: an indispensable biomarker for older adults. Clin Interven Aging 2019;14:1681. doi: https://doi.org/10.2147/CIA.S194543.
[23] Syddall H, Cooper C, Martin F, Briggs R, Aihie Sayer A. Is grip strength a useful single marker of frailty? Age Ageing 2003;32:650–6. doi: https://doi.org/10.1093/ageing/afg111.
[24] Bohannon RW. Hand-grip dynamometry predicts future outcomes in aging adults. J Geriatr Phys Ther 2008;31:3–10. doi: https://doi.org/10.1519/00139143-200831010-00002.
[25] Taekema DG, Gussekloo J, Maier AB, Westendorp RG, de Craen AJ. Handgrip strength as a predictor of functional, psychological and social health. A prospective population-based study among the oldest old. Age Ageing 2010;39:331–7. doi: https://doi.org/10.1093/ageing/afq022.
[26] Peralta M, Dias CM, Marques A, Henriques-Neto D, Sousa-Uva M. Longitudinal association between grip strength and the risk of heart diseases among European middle-aged and older adults. Exp Gerontol 2023;171:. doi: https://doi.org/10.1016/j.exger.2022.112014112014.
[27] Wu Y, Wang W, Liu T, Zhang D. Association of grip strength with risk of all-cause mortality, cardiovascular diseases, and cancer in community-dwelling populations: a meta-analysis of prospective cohort studies. JAMDA 2017;18:551–e17. doi: https://doi.org/10.1016/j.jamda.2017.03.011.
[28] Syddall HE, Westbury LD, Dodds R, Dennison E, Cooper C, Sayer AA. Mortality in the Hertfordshire Ageing Study: association with level and loss of hand grip strength in later life. Age Ageing 2017;46:407–12. doi: https://doi.org/10.1093/ageing/afw222.
[29] Adamo DE, Anderson T, Koochaki M, Fritz NE. Declines in grip strength may indicate early changes in cognition in healthy middle-aged adults. PLoS One 2020;15. doi: https://doi.org/10.1371/journal.pone.0232021.
[30] Sternäng O, Reynolds CA, Finkel D, Ernsth-Bravell M, Pedersen NL, Dahl Aslan AK. Grip strength and cognitive abilities: associations in old age. J Gerontol B: Psychol Sci Soc Sci 2016;71:841–8. doi: https://doi.org/10.1093/geronb/gbv017.
[31] Carson RG. Get a grip: individual variations in grip strength are a marker of brain health. Neurobiol Aging 2018;71:189–222. doi: https://doi.org/10.1016/j.neurobiolaging.2018.07.023.
[32] Bikbov MM, Zainullin RM, Gilmanshin TR, Iakupova EM, Kazakbaeva GM, Panda-Jonas S, et al. Hand grip strength and ocular associations: the Ural Eye and Medical Study. BJO 2022. doi: https://doi.org/10.1136/bjo-2022-321404.

[33] Kim SH, Hurh K, Park Y, Jang SI, Park EC. Synergistic associations of visual and self-reported hearing acuity with low handgrip strength in older adults: a population-based cross-sectional study. BMC Geriatr 2021;2021(21):1–12. doi: https://doi.org/10.1186/s12877-021-02470-w.
[34] Christensen H, Mackinnon AJ, Korten A, Jorm AF. The" common cause hypothesis" of cognitive aging: evidence for not only a common factor but also specific associations of age with vision and grip strength in a cross-sectional analysis. Psychol Aging 2001;16:588. doi: https://doi.org/10.1037/0882-7974.16.4.588.
[35] Li KZ, Lindenberger U. Relations between aging sensory/sensorimotor and cognitive functions. Neurosci Biobehav Rev 2002;26:777–83. doi: https://doi.org/10.1016/S0149-7634(02)00073-8.
[36] Lindenberger U, Ghisletta P. Cognitive and sensory declines in old age: gauging the evidence for a common cause. Psychol Aging 2009;24:1. doi: https://doi.org/10.1037/a0014986.
[37] Whelan BJ, Savva GM. Design and methodology of the Irish Longitudinal Study on Ageing. J Am Geriatr Soc 2013;61:S265–8. doi: https://doi.org/10.1111/jgs.12199.
[38] Genolini C, Alacoque X, Sentenac M, Arnaud C. kml and kml3d: R packages to cluster longitudinal data. J Stat Softw 2015;65:1–34. , https://www.jstatsoft.org/article/view/v065i04.
[39] Matthews S, Ward M, Nolan A, Normand C, Kenny RA, May P. Predicting mortality in The Irish Longitudinal Study on Ageing (TILDA): development of a four-year index and comparison with international measures. BMC Geriatr 2022;22:1–11. doi: https://doi.org/10.1186/s12877-022-03196-z.
[40] Bolognini N, Rossetti A, Casati C, Mancini F, Vallar G. Neuromodulation of multisensory perception: a tDCS study of the sound-induced flash illusion. Neuropsychologia 2011;49:231–7. doi: https://doi.org/10.1016/j.neuropsychologia.2010.11.015.
[41] Watkins S, Shams L, Tanaka S, Haynes JD, Rees G. Sound alters activity in human V1 in association with illusory visual perception. Neuroimage 2006;31:1247–56. doi: https://doi.org/10.1016/j.neuroimage.2006.01.016.
[42] Hirst RJ, Whelan R, Boyle R, Setti A, Knight S, O'Connor J, et al. Gray matter volume in the right angular gyrus is associated with differential patterns of multisensory integration with aging. Neurobiol Aging 2021;100:83–90.
[43] Hamilton RH, Wiener M, Drebing DE, Coslett HB. Gone in a flash: manipulation of audiovisual temporal integration using transcranial magnetic stimulation. Front Psychol 2013;4:571. doi: https://doi.org/10.3389/fpsyg.2013.00571.
[44] Kamke MR, Vieth HE, Cottrell D, Mattingley JB. Parietal disruption alters audiovisual binding in the sound-induced flash illusion. Neuroimage 2012;62:1334–41. doi: https://doi.org/10.1016/j.neuroimage.2012.05.063.
[45] Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv*. 2014; 1406: 5823. doi: 10.48550/arXiv.1406.5823.
[46] Team R. (2021). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria. https://www.R-project.org/
[47] Caliński T, Harabasz J. A dendrite method for cluster analysis. Commun Stat 1974;3:1–27. doi: https://doi.org/10.1080/03610927408827101.
[48] Hirst RJ, Setti A, Kenny RA, Newell FN. Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception. Sci Rep 2019;9:1–12. doi: https://doi.org/10.1038/s41598-019-55901-5.
[49] Shams L, Ma WJ, Beierholm U. Sound-induced flash illusion as an optimal percept. Neuroreport 2005;16:1923–7. doi: https://doi.org/10.1097/01.wnr.0000187634.68504.bb.
[50] Wise A, Barnett-Cowan M. Perceived simultaneity and temporal order of audiovisual events following concussion. Front Human Neurosci 2018;139. doi: https://doi.org/10.3389/fnhum.2018.00139.
[51] Ward NS, Swayne OB, Newton JM. Age-dependent changes in the neural correlates of force modulation: an fMRI study. Neurobiol Aging 2008;2008(29):1434–46. doi: https://doi.org/10.1016/j.neurobiolaging.2007.04.017.
[52] Noble JW, Eng JJ, Kokotilo KJ, Boyd LA. Aging effects on the control of grip force magnitude: an fMRI study. Exp Gerontol 2011;46:453–61. doi: https://doi.org/10.1016/j.exger.2011.01.004.
[53] Seidler RD, Bernard JA, Burutolu TB, Fling BW, Gordon MT, Gwin JT, et al. Motor control and aging: links to age-related brain structural, functional, and biochemical effects. Neurosci Biobehav Rev 2010;34(5):721–33.
[54] Seidler R, Erdeniz B, Koppelmans V, Hirsiger S, Mérillat S, Jäncke L. Associations between age, motor function, and resting state sensorimotor network connectivity in healthy older adults. Neuroimage 2015;108:47–59. doi: https://doi.org/10.1016/j.neuroimage.2014.12.023.
[55] Hirsiger S, Koppelmans V, Mérillat S, Liem F, Erdeniz B, Seidler RD, et al. Structural and functional connectivity in healthy aging: associations for cognition and motor behavior. Hum Brain Mapp 2016;37:855–67. doi: https://doi.org/10.1002/hbm.23067.
[56] Chou M-Y, Nishita Y, Nakagawa T, Tange C, Tomida M, Shimokata H, et al. Role of gait speed and grip strength in predicting 10-year cognitive decline among community-dwelling older people. BMC Geriatr 2019;19(1). doi: https://doi.org/10.1186/s12877-019-1199-7.
[57] Cui M, Zhang S, Liu Y, Gang X, Wang G. Grip strength and the risk of cognitive decline and dementia: a systematic review and meta-analysis of longitudinal cohort studies. Front Aging Neurosci 2021;13:. doi: https://doi.org/10.3389/fnagi.2021.625551625551.
[58] Fritz NE, McCarthy CJ, Adamo DE. Handgrip strength as a means of monitoring progression of cognitive decline–A scoping review. Ageing Res Rev 2017;35:112–23. doi: https://doi.org/10.1016/j.arr.2017.01.004.
[59] Ismail SS, Mohamad M, Syazarina SO, Nafisah WY. Hand grips strength effect on motor function in human brain using fMRI: a pilot study. J Phys: Conf 2014;546:. doi: https://doi.org/10.1088/1742-6596/546/1/012005012005.
[60] Cramer SC, Weisskoff RM, Schaechter JD, Nelles G, Foley M, Finklestein SP, et al. Motor cortex activation is related to force of squeezing. Hum Brain Mapp 2002;16:197–205. doi: https://doi.org/10.1002/hbm.10040.
[61] Moeller K, Willmes K, Klein E. A review on functional and structural brain connectivity in numerical cognition. Front Human Neurosci 2015;9:227. doi: https://doi.org/10.3389/fnhum.2015.00227.
[62] Wiener M, Turkeltaub P, Coslett HB. The image of time: a voxel-wise meta-analysis. Neuroimage 2010;49:1728–40. doi: https://doi.org/10.1016/j.neuroimage.2009.09.064.
[63] Suárez-Méndez I, Doval S, Walter S, Pasquín N, Bernabé R, Gallo EC, et al. Functional connectivity disruption in frail older adults without global cognitive deficits. Front Med 2020;7. doi: https://doi.org/10.3389/fmed.2020.00322.
[64] Suárez-Méndez I, Walter S, López-Sanz D, Pasquín N, Bernabé R, Castillo Gallo E, et al. Ongoing oscillatory electrophysiological alterations in frail older adults: a MEG study. Front Aging Neurosci 2021;13:. doi: https://doi.org/10.3389/fnagi.2021.609043609043.
[65] Seghier ML. The angular gyrus: multiple functions and multiple subdivisions. Neuroscientist 2013;19:43–61. doi: https://doi.org/10.1177/1073858412440596.
[66] Hicks GE, Shardell M, Alley DE, Miller RR, Bandinelli S, Guralnik J, et al. Absolute strength and loss of strength as predictors of mobility decline in older adults: the InCHIANTI study. J Gerontol A: Bio Sci Med Sci 2012;67A(1):66–73.
[67] Forrest KY, Williams AM, Leeds MJ, Robare JF, Bechard TJ. Patterns and correlates of grip strength in older Americans. Curr Aging Sci 2018;11:63–70. doi: https://doi.org/10.1093/gerona/glr055.
[68] Deary IJ, Johnson W, Gow AJ, Pattie A, Brett CE, Bates TC, et al. Losing one's grip: a bivariate growth curve model of grip strength and nonverbal reasoning from age 79 to 87 years in the Lothian Birth Cohort 1921. J Geront B: Psychol Sci Soc Sci 2011;66:699–707. doi: https://doi.org/10.1093/geronb/gbr059.
[69] Ritchie SJ, Tucker-Drob EM, Starr JM, Deary IJ. Do cognitive and physical functions age in concert from age 70 to 76? Evidence from the Lothian Birth Cohort 1936. Span J Psychol 2016;19.
[70] Chan JS, Wibral M, Stawowsky C, Brandl M, Helbling S, Naumer MJ, et al. Predictive coding over the lifespan: increased reliance on perceptual priors in older adults—a magnetoencephalography and dynamic causal modeling study. Front Aging Neurosci 2021;13:631599. doi: https://doi.org/10.3389/fnagi.2021.631599.