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Individual Differences in Ageing, Cognitive Status, and Sex on Susceptibility to the Sound-Induced Flash Illusion: A Large-Scale Study

Belinda Hernández
Trinity College Dublin and St. James Hospital, Dublin, Ireland

Annalisa Setti
University College Cork

Rose Anne Kenny
Trinity College Dublin and St. James Hospital, Dublin, Ireland

Fiona N. Newell
Trinity College Dublin

Although there is some evidence suggesting that audiovisual integration is inefficient in older adults, and that such inefficiency is associated with age-related functions such as mild cognitive impairment, falls, and balance maintenance, these associations have yet to be demonstrated in a population-representative study of ageing. Based on a sample of 3,955 adults aged over 50 years, we investigated the role of age, cognitive status, and sex on susceptibility to the sound-induced flash illusion (SIFI) as a measure of audiovisual temporal integration, while controlling for a range of covariates. We developed a hierarchical Bayesian, ordinal-regression model to determine which variables predicted audiovisual integration. Higher susceptibility to the SIFI was predicted by older age, female sex (at larger temporal asynchronies), and a lower score on the Montreal Cognitive Assessment (MoCA). Our results confirm, in a population-representative sample, that enhanced audiovisual integration is associated with ageing and extend the association between multisensory integration and mild cognitive impairment to global cognitive status. Importantly, the findings also highlight the role of the sex of the participant as a previously overlooked factor in studying multisensory perception in ageing.

Keywords: sound-induced flash illusion, multisensory, ageing, mild cognitive impairment, audiovisual

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As the world constantly provides multiple sensory inputs, the brain combines these inputs into perceptual representations (Wallace & Stein, 1997). Multisensory perception, that is, the ability to combine information from the different senses to achieve a coherent perception of the environment (Calvert, Spence, & Stein, 2004), is fundamental to cognitive function, as demonstrated by the occurrence of multisensory deficits in autism, dyslexia, and mild cognitive impairment (MCI; J. S. Chan et al., 2015; Noel, Stevenson, & Wallace, 2018). Moreover, multisensory integration has emerged in the past 20 years as a predictor of cognitive performance and functional abilities in ageing (Alais, Newell, & Mamassian, 2010; de Dieuleveult, Siemonsma, van Erp, & Brouwer, 2017; Freiherr, Lundström, Habel, & Reetz, 2013; Murray, Lewkowicz, Amedi, & Wallace, 2016). Therefore, multisensory perception could provide a unique contribution to the understanding of the ageing process and the development of novel screening tools for cognitive and functional impairment (J. S. Chan, Connolly, & Setti, 2018; Murray et al., 2018; Setti, Burke, et al., 2011).

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Belinda Hernández, The Irish Longitudinal Study in Ageing, Trinity College Dublin, and Mercer Institute for Successful Ageing, St. James Hospital, Dublin, Ireland; Annalisa Setti, School of Applied Psychology, University College Cork; Rose Anne Kenny, The Irish Longitudinal Study in Ageing, Trinity College Dublin, and Mercer Institute for Successful Ageing, St. James Hospital; Fiona N. Newell, School of Psychology and Institute of Neuroscience, Trinity College Dublin.

Belinda Hernández and Annalisa Setti are joint first authors.

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Correspondence concerning this article should be addressed to Annalisa Setti, School of Applied Psychology, University College Cork, North Mall Enterprise Centre, Cork T12 K8AF, Ireland. E-mail: a.setti@ucc.ie

Multisensory Integration and Ageing

With ageing, the quality of information coming from each of the senses to the brain deteriorates (Crews & Campbell, 2004; Fozard & Gordon-Salant, 2001; Humes, Busey, Craig, & Kewley-Port, 2009; Lee, Smith, & Kington, 1999; Lindenberger & Baltes, 1994; Lindenberger & Ghisletta, 2009; Owsley, 2011; Schieber, 2006) and cognitive processing speed slows down (Salthouse, 1996, 2009). The corticothalamic loops involved in sensory and cognitive processing are affected by ageing (Fama & Sullivan, 2015). Among the compensatory strategies for perceptual and cognitive decline (Barulli & Stern, 2013; Cabeza, Anderson, Locantore, & McIntosh, 2002), two are of interest here: the first is reliance on world knowledge (Pichora-Fuller, 2008; Pichora-Fuller & Souza, 2003; Tye-Murray, Sommers, Spehar, Myerson, & Hale, 2010; Tye-Murray et al., 2008) and past experience, that is, on perceptual priors and templates predicting what a given situation should look or sound or feel like (J. S. Chan et al., 2017; Y. M. Chan, Pianta, Bode, & McKendrick, 2017). The second strategy is a relaxation of the criteria for integration of stimuli with given physical characteristics (e.g., location and timing) to increase reliance on multiple sensory inputs (Murray et al., 2016). For example, inputs that are separated in time by a few hundred milliseconds could still be integrated. This relaxation of the criteria for multisensory integration could be a consequence of the slowing of unisensory processing, although is not fully explained by it (Laurienti, Burdette, Maldjian, & Wallace, 2006). For example, visual sensory dominance, which is typically characteristic of perception in children, decreases in older adults (Murray et al., 2018), whereas auditory inputs become essential for adaptively responding to the environment (Campos, Ramkhalawansingh, & Pichora-Fuller, 2018; Paraskevoudi, Balcı, & Vatakis, 2018). Evidence from neuropsysiological (Stein & Meredith, 1993) and behavioral studies (Sumby & Pollack, 1954) suggest a large benefit for multisensory over unisensory inputs on perception, often referred to as *superadditive* performance. Indeed, unisensory discrimination thresholds do not exclusively predict the ability to integrate information across the senses in older adults, whereas it does in younger adults (Stevenson, Baum, Krueger, Newhouse, & Wallace, 2018). Moreover, perception in older adults benefits more from multisensory inputs than in younger adults (Laurienti et al., 2006; Mozolic, Hugenschmidt, Peiffer, & Laurienti, 2012; Peiffer, Mozolic, Hugenschmidt, & Laurienti, 2007). When congruent stimuli from different modalities are presented simultaneously, and response times are utilized as a measure of processing efficiency, a greater benefit on perception for multisensory over unisensory stimuli has been found in older adults (e.g., Bucur, Allen, Sanders, Ruthruff, & Murphy, 2005; Laurienti et al., 2006). Depending on the nature of the study, this benefit is often supported by evidence for a violation of the race model inequality compared with unisensory response times (Gondan & Minakata, 2016; Miller, 1982), whereby the speed of a response to a multisensory input is more likely to be faster than that predicted from the summation of probabilities of a fast response to an input from each modality.

However, inputs from different senses, even when coming from the same source in the environment, do not reach the senses at the same time, for example, because of the speed of light and of sound, and have different transduction times. Therefore, to allow for efficient integration of inputs from different modalities, the brain uses a temporal window within which integration can occur, referred to as the *temporal binding window* (TBW; Vroomen & Keetels, 2010). Furthermore, the width of this TBW increases with ageing to maximize the opportunity of perception benefitting from multisensory inputs when the rates of sensory transduction may decline (Colonius & Diederich, 2004; Diederich, Colonius, & Schomburg, 2008). Although this increased leeway in combining incoming sensory inputs may be considered adaptive, and is efficient when the inputs belong to the same object or event, it is maladaptive when the inputs do not (Setti, Burke, Kenny, & Newell, 2011; Stevenson et al., 2018). The results from tasks that have systematically manipulated the temporal delay between inputs from different modalities, and utilized categorical responses instead of response times, have suggested that the TBW may be overextended in older adults (e.g., Setti, Burke, et al., 2011). However, there are important individual differences within the older adult population. For example, although inefficient multisensory processing is related to falling (Mahoney, Cotton, & Verghese, 2018; Mahoney & Verghese, 2018; Setti, Burke, et al., 2011), older adults who are healthy and exercise regularly show more efficient multisensory processing (O'Brien, Ottoboni, Tessari, & Setti, 2017).

The extant literature indicates that understanding what constitutes a "normal" pattern of integration in different population groups is a crucial issue in understanding why multisensory integration, although potentially beneficial for perception (Mahoney, Li, Oh-Park, Verghese, & Holtzer, 2011), is also associated with decline in a number of age-related functions (de Dieuleveult et al., 2017; Setti, Burke, et al., 2011; Setti, Finnigan, et al., 2011).

The sound-induced flash illusion (SIFI; Shams, Kamitani, & Shimojo, 2000, 2002), in which the co-occurrence of one visual stimulus ("flash") with two auditory stimuli ("beeps") results in the illusory perception of two visual stimuli, has been utilized a measure of multisensory integration. The SIFI has been ascribed to early sensory processing (Bhattacharya, Shams, & Shimojo, 2002; Shams, Kamitani, Thompson, & Shimojo, 2001; Watkins, Shams, Tanaka, Haynes, & Rees, 2006) and described by neurocomputational models based on Bayesian inference (Cuppini, Shams, Magosso, & Ursino, 2017). Importantly, the delay between the beeps can be manipulated to reveal the temporal window during which the illusion is experienced. Young adults typically perceive the illusion within a restricted TBW of 100 ms (Shams et al., 2002); however, older adults perceive the illusion at much longer stimulus onset asynchronies (SOAs; DeLoss, Pierce, & Andersen, 2013; McGovern, Roudaia, Stapleton, McGinnity, & Newell, 2014; Setti, Burke, et al., 2011). This implies that older adults have a higher chance to integrate incongruent inputs over time. Greater susceptibility to multisensory interactions in older adults has been reported to other multisensory illusions (Bedard & Barnett-Cowan, 2016), also relating to the TBW size. Age differences in neural processing between younger and older adults have been shown in temporal order judgment tasks, which are associated with the TBW (e.g., Basharat, Adams, Staines, & Barnett-Cowan, 2018; Scurry, Vercillo, Nicholson, Webster, & Jiang, 2019; Setti, Finnigan, et al., 2011). Greater susceptibility to the SIFI at longer SOAs in older more than younger adults has also been linked to higher reliance on perceptual priors (J. S. Chan et al., 2017). In a magnetoencephalography study, older adults showed increased β band prestimulus in the trials presenting the SIFI, indicating the generation of predictions on the stimulus to be presented (J. S. Chan et al., 2017). Therefore, this illusion captures well the two adaptive strategies in older adults' brains to maintain an efficient perception of the environment, namely, a larger TBW and greater reliance on perceptual history or priors, as well as the potentially negative consequences of such strategies (Baum & Stevenson, 2017).

To summarize, the ability to assess or measure the efficiency with which information is integrated across the senses in any individual could potentially lead to a new diagnostic tool that can discriminate healthy and pathological ageing (de Dieuleveult et al., 2017; Murray et al., 2018), possibly at early stages of decline. Such knowledge may lead to a new avenue for designing of brain-training interventions over the life span (Mozolic, Hayasaka, & Laurienti, 2010), as supported by evidence suggesting plastic changes in the brain obtained with training programs targeting general multisensory integration (Setti et al., 2014) and balance control (Merriman, Whyatt, Setti, Craig, & Newell, 2015) on the susceptibility to the SIFI.

Although the results to date indicate that multisensory processing is a strong candidate for detecting brain and behavioral changes characterizing healthy ageing, and a potential new marker for pathological ageing, it is important to note that all the available studies are experimental in nature, mostly involving small number of participants. In an exception, a study on multisensory perception included a sample of 220 participants aged 7 to 86 and found that the size of the TBW is larger in children and older adults, indicating a U-shaped developmental trajectory across the life span (Noel, De Niear, Van der Burg, & Wallace, 2016). In another large study on falls (Mahoney et al., 2018), visual-proprioceptive integration was studied on a sample of 289 older adults, showing that older adults with efficient integration abilities were less prone to falling over a period of approximately 2 years. However, to understand the unique and causative role of multisensory integration on ageing in more detail, it is necessary to investigate these effects in population-representative samples, ideally over a number of years; therefore, longitudinal population studies are necessary.

Our study presents the first (cross-sectional) data from the SIFI as introduced in the population representative study The Irish Longitudinal Study on Ageing (TILDA), assessing multisensory perception (using the SIFI) in a large sample of older adults, with a planned follow-up 3 years after the data collection reported in this study.

Previous studies of similar kind, such as The Berlin Ageing Study (Ghisletta & Lindenberger, 2003; Lindenberger & Baltes, 1997; Lindenberger & Ghisletta, 2009), the Health and Retirement Study, the English Longitudinal Study on Ageing, and the Cognitive Function and Ageing Study (C-FAS), have established a close association between sensory and cognitive ageing (Li & Lindenberger, 2002; Lindenberger, Scherer, & Baltes, 2001). However, the strong association at the cross-sectional level likely overestimates the causal link between deteriorated sensory processing and cognitive decline, and thus suggests that the association may be due to more efficient perceptual discrimination in individuals with preserved cognitive abilities (Lindenberger, von Oertzen, Ghisletta, & Hertzog, 2011). Nevertheless, population studies have demonstrated that sensory decline can be predictive of cognitive decline and dementia (Lin et al., 2011, 2013; Singer, Verhaeghen, Ghisletta, Lindenberger, & Baltes, 2003), indicating that poor sensory performance is a potential risk factor for cognitive impairment. However, although everyday perception is arguably based on multisensory processing, an investigation of the link between multisensory processing and ageing in a large population-representative study had not previously been conducted.

Aims of the Study

In the present study, we present results from a population-representative, cross-sectional study that represents the first study of this kind worldwide to include an assessment of multisensory perceptual function, as measured through susceptibility to the SIFI, in older adults.

The main aim of the present study was to assess whether ageing is associated with changes in multisensory processing, specifically, susceptibility to the SIFI.

A second aim was to determine whether there are sex differences in multisensory processing efficiency in our sample. As an individual difference, the sex of the participant has received little attention in studies of perceptual function, specifically in studies of multisensory processing (Barnett-Cowan, Dyde, Thompson, & Harris, 2010), likely assuming that basic integration processes are the same for both females and males. Nonetheless, some studies have reported interesting sex differences in perception, including in temporal order threshold within the auditory domain (Wittmann & Szelag, 2003), speech perception (Alm & Behne, 2015), and the perception of temporal interval segmentation (Szelag, 1997), which could be related to temporal precision (Pöppel, 1997). Important sex differences emerge across a range of functions with ageing, in particular, older females are more prone to falling, even when physical differences between the sexes are taken into account (Duckham et al., 2013; Gale, Cooper, & Aihie Sayer, 2016), and a higher prevalence of MCI and diagnosis of Alzheimer's disease is reported in older females than males (see, e.g., Li & Singh, 2014).

Finally, our aim was to elucidate the association between multisensory function and cognitive performance, as measured using the Montreal Cognitive Assessment (MoCA). Indeed, it has been suggested that deficits in temporal discrimination within (Humes, Kewley-Port, Fogerty, & Kinney, 2010) and across the senses can lead to cognitive deficits (Foss-Feig et al., 2010). The results from a previous study suggest that multisensory integration deficits, that is, higher susceptibility at the SIFI of 200 ms and 300 ms, but not 500 ms, are associated with MCI, as assessed by the Consortium to Establish a Registry for Alzheimer's Disease (CERAD) battery (J. S. Chan et al., 2015). J. S. Chan et al. (2015) suggested that this association could be due to several attentional or perceptual factors, including increased susceptibility to distraction (Burgess & Braver, 2010; Mozolic, Long, Morgan, Rawley-Payne, & Laurienti, 2011) or decreased inhibition of irrelevant stimuli at sensory (Mozolic et al., 2011) and perceptual levels (Melnick, Harrison, Park, Bennetto, & Tadin, 2013; Rey-Mermet & Gade, 2018), whereas it was not likely due to overall processing speed (Salthouse, 1996). Alternatively, increased SIFI susceptibility could be due to malfunctioning of the "internal clock," as temporal discrimination and integration may be related to a central timing mechanism (Ivry & Spencer, 2004), which, in turn, is thought to be related to cognitive function and declines with ageing (Nowak et al., 2016; Szelag & Skolimowska, 2012), although temporal acuity does not always explain multisensory integration (Stevenson et al., 2018). Taken together, these findings suggest a link between multisensory perception and global cognition; consequently, we hypothesized that higher susceptibility to the SIFI would be associated with lower scores on the MoCA.

Method

Participants

Participants were drawn from the third wave of TILDA, a population representative sample of individuals aged 50 and over from across the Republic of Ireland. Details of the sampling design have been provided in a previous study (Whelan & Savva, 2013). The study was approved by the Trinity College Faculty of Health Sciences Ethics Committee, and testing protocols conformed to the Declaration of Helsinki (1964). All participants provided written, informed consent when they first participated in the study (at Wave 1), and both written and verbal consent were repeated at Wave 3 (the focus of this study). Respondents in all cases were provided with copies of their signed consent forms.

A total of 4,309 participants took part in the health assessment, 3,955 of which were included in the results presented here. Of the remaining 354 participants, 296 did not take part in the SIFI assessment and an additional 58 participants were excluded, as they were either registered as legally blind (and therefore not eligible for testing with the SIFI) or some of their data for covariates was incomplete. Table 1 shows the breakdown of participants by age, sex, and education.

Material and Measures

Cross-sectional data from only Wave 3 of TILDA were acquired for this study, as the SIFI assessment was introduced in this wave of the project. The protocol and tests utilized for the TILDA study are described elsewhere (Whelan & Savva, 2013). For the SIFI, the stimuli utilized in TILDA were those used in previous studies (Setti, Burke, et al., 2011). Specifically, the visual stimulus ("flash") comprised a white disk, subtending a visual angle of approximately 1.5° and luminance of approximately 32 foot-lambert, projected onto a black background 5 cm below the central fixation cross. This white disk was projected for 16 ms. Each auditory "beeps" stimulus was a brief burst of 3,500-Hz sounds (10 ms, 1 ms ramp), with the volume set at approximately 80 dB. The auditory-only trials were presented together in one single block comprising two beeps (2B0F) presented at SOAs of 70, 150, and 230 ms; participants were instructed to verbally report the number of beeps heard in each trial. The auditory-only block of trials was presented following a mixed block of multisensory (illusory and congruent) and unisensory visual trials, which were interleaved. During the illusory trials, one flash was presented simultaneously with one beep, and the second beep either preceded (A-VA) or followed (VA-A) the simultaneous beep/flash with an SOA of either 70, 150, or 230 ms. We hitherto collectively refer to the SOA conditions in which the beep preceded the bimodal stimulus as negative SOAs (i.e., 2B1F–) and the conditions in which the beep followed the bimodal stimulus as positive SOAs (i.e., 2B1F+; see Setti, Burke, et al., 2011, for similar nomenclature). Nonillusory (multisensory congruent) control trials were also introduced, which included the following multisensory combinations: one beep and one flash (1B1F); two beeps and two flashes (2B2F) presented at SOAs of 70, 150, or 230 ms. The unisensory visual trials comprised of two flashes (0B2F) presented at an SOA of 70 ms. In the mixed block of trials, the participant was instructed to verbally report the number of flashes they perceived, and ignore the beeps, while the research nurse pressed the keyboard. In every condition, each trial was presented twice in random order across participants. There was a practice phase before the testing, comprising one trial from each of the following conditions: 2B1F+ (SOAs of 70, 150, and 230), 1B1F, 2F0B, 2F2B, and auditory-only trials (1B0F; 2B0F with SOAs of 70, 150, and 230).

Procedure

The SIFI was included as part of a larger health assessment within TILDA comprising a number of health, cognitive, and visual tests for a total duration of approximately 3 hr. All assessments were carried out by trained health nurses. A standard operating procedure was implemented throughout the testing. For the SIFI assessment specifically, participants were asked to sit in front of a computer (Dell Latitude E6400 with Intel Core 2 Duo CPU, 2Gb RAM, using Windows 7 Professional OS). First, the task was explained to the participants and they were instructed to look at the fixation cross at the center of the screen, had the opportunity to practice with a practice block, and then invited to start the experiment. The nurse sat near the participant and recorded the participant's response to each trial by pressing the key corresponding to the number reported by the participant. Verbal reporting was conducted to avoid problems for participants not accustomed to keyboards. Each trial was initiated by pressing the space bar. A fixation cross appeared for 1,000 ms, to which the participant was instructed to attend, and then the stimuli were delivered. Once a response was provided, the space bar had to be pressed to continue to the next trial. Hence, the experiment was self-paced.

Data Analyses

In order to predict susceptibility to the SIFI and therefore determine statistically significant predictors of audiovisual integration, we developed a hierarchical Bayesian model, which is discussed in detail in The Statistical Model section. The code to run the model was developed by the authors using the R statistical programming language and run using R Version 3.4.2 (R Core Team, 2017).

Table 1
Number of Participants by Age, Sex, and Education

Variable	Men *n* = 1,759 (44.48%)	Women *n* = 2,196 (55.52%)	Total *n* = 3,955 (100%)
Age (years), *n* (%)			
50–64	894 (50.82)	1,207 (54.96)	2,101 (53.12)
65–74	608 (34.57)	741 (33.74)	1,349 (34.11)
75+	257 (14.61)	248 (11.29)	505 (12.77)
Education, *n* (%)			
None/primary	353 (20.07)	328 (14.94)	681 (17.22)
Secondary	711 (40.42)	881 (40.12)	1,592 (40.25)
Third/higher	695 (39.51)	987 (44.95)	1,682 (42.53)

In order to assess whether age, sex, and cognition are associated with less efficient multisensory processing, the following predictor variables were included in the model for each experimental condition: age, MoCA, sex, and SOA. Education was introduced as a known factor influencing cognitive performance. As ageing is related to the deterioration of unisensory processes as well as audiovisual integration, hearing ability and visual acuity were also controlled for by including the self-reported question on hearing ("Is your hearing? . . . excellent, very good, good, fair, poor?"; see Kenny Gibson, Cronin, Kenny, & Setti, 2014) and vision ("Is your vision? . . . excellent, very good, good, fair, poor, or are you registered as legally blind?"). Participants' performance on the 0B2F was introduced to control for visual processing speed, and the 1B1F condition was introduced to control for baseline performance.

The Statistical Model

The dependent variable was the number of correct responses the respondent gave over the total number of trials (with two trials per condition). Therefore, three response outcomes are possible for each condition: "0," that is, the number of flashes (or beeps in the auditory-only block) was not correctly identified in either trial; "1," that is, the number flashes/beeps was correctly identified in one of two trials; or "2," the number of flashes/beeps was correctly identified in both trials. The response variable in this instance is therefore ordinal, as there are a finite number of options (0, 1, or 2 correct responses in this case), and the value of the response has a numeric interpretation, that is, $2 > 1 > 0$. Therefore, to model the number of successful responses (correct answers by the participants over two trials), it is assumed that the number of correct responses follows a binomial distribution, with some probability of being correct for each trial replication, which we refer to as p over a given number of trials k, where $k = 2$ in this instance.

As previously described, conditions involving two beeps were tested with SOAs of 70, 150, and 230 ms. Therefore, this experimental design has a nested structure for each experimental condition, in which each person $j = 1..n^{(l)}$ has three repeated observations (one at each SOA for the condition in which the beep preceded or followed the flash), where $n^{(l)}$ refers to the number of participants for which there was full data for experimental condition l. As repeated observations of the same participant are likely to be closely correlated, that is, observations within an individual are likely to be more similar to each other than observations between two individuals, this correlation structure has to be accounted for in the model design. In order to account for such correlation, we developed a hierarchical Bayesian ordinal regression model.

The overall model for each condition l can be summarized as follows:

$$\begin{aligned} \text{successes}_{ij} &\sim Bin(p_{ij}) \\ \text{logit}(p_{ij}) &= \alpha + x_{ij}^{t}\beta + U_j + \epsilon_{ij}, \end{aligned} \quad (1)$$

where p_{ij} refers to the probability of success for participant j at SOAs of $i = 70$ ms, 150 ms, and 230 ms; α is the model intercept, x_{ij} refers to the vector of fixed effects covariates included in the model, which are discussed in the Data Analysis section, U_j is a random effect for participant j, β is the vector of coefficients corresponding to the fixed effects, and ϵ_{ij} are the residual errors.

In order to fully specify this model, priors have to be placed on all unknown parameters. In this case, uninformative priors were placed on all the unknown parameters (i.e., no prior knowledge is assumed). More formally,

$$\begin{aligned} U_j &\sim N(0, \tau_j^{-2}) \\ \tau_j &\sim Ga(0.01, 0.01) \\ \beta &\sim DoubleExp(0, \tau_\beta^{-2}) \\ \tau_\beta &\sim Ga(0.001, 0.001). \end{aligned} \quad (2)$$

As the TILDA sample itself is a multiclustered sample, whereby participants are nested within geographical clusters, which were themselves clustered by socioeconomic status (SES), other models were also run to account for random effects of cluster and SES, but they are not included here and were found not to affect the results presented in this article.

All the models discussed in the following sections had a burn in of 2,000 iterations, and the posterior distributions of all model parameters were estimated using the following 5,000 iterations across three chains. In all cases, convergence of the trace plots for each of the parameters was assessed and verified.

Results

Figure 1 shows the odds ratios and 95% credible intervals (CIs) for the two illusion conditions, 2B1F+ and 2B1F–, in which a single beep followed or preceded the bimodal stimulus, respectively. A variable is thought to be significantly related to the number of correct responses identified over the two trials if its 95% CI for the odds ratio does not overlap with 1 (see the vertical line in Figure 1). The mean, standard deviation, and 95% CIs for the odds ratios for each of these four experimental conditions are presented in numerical form in Tables S.1 to S.4 of the online supplemental materials; Figure S.1 of the online supplemental materials shows the odds ratios and 95% CIs for the coefficients of the predictor variables for the two control conditions (2B0F and 2B2F).

As can be seen in Figure 1, the results for both illusion conditions are similar.

With respect to the SOA, longer SOAs were associated with greater susceptibility to the SIFI (i.e., fewer correct responses; 20% of participants responded to both trials correctly at SOAs of 150 and 230 ms; 40% responded at an SOA of 70 ms), which likely indicates a near-random response when the stimuli are very rapidly presented and a robust susceptibility to the illusion at longer SOAs. For the illusion 2B1F+ condition, the odds of correctly identifying one flash at 150 ms compared with 70 ms were 0.03 (95% CI [0.013, 0.048]) and 0.004 (95% CI [0.002, 0.008]) at 230 ms compared with 70 ms. These results were very similar to those for the 2B1F– condition (odds ratio of 0.014 and 0.004 for SOAs of 150 ms and 230 ms, respectively). As the SIFI has been ascribed to the higher reliability of audition over vision in the temporal domain (Shams et al., 2000), we analyzed performance on the 2B0F condition. The odds of participants correctly identifying two beeps at an SOA of 150 ms compared with 70 ms were 5.5 (95% CI [1.6, 12.6]) and 6.5 (95% CI [1.3, 20.6]) for an SOA of 230 ms compared with 70 ms (see Figure S.1 of the online supplemental materials); thus, SOA was not a significant predictor in the 2F2B control condition.

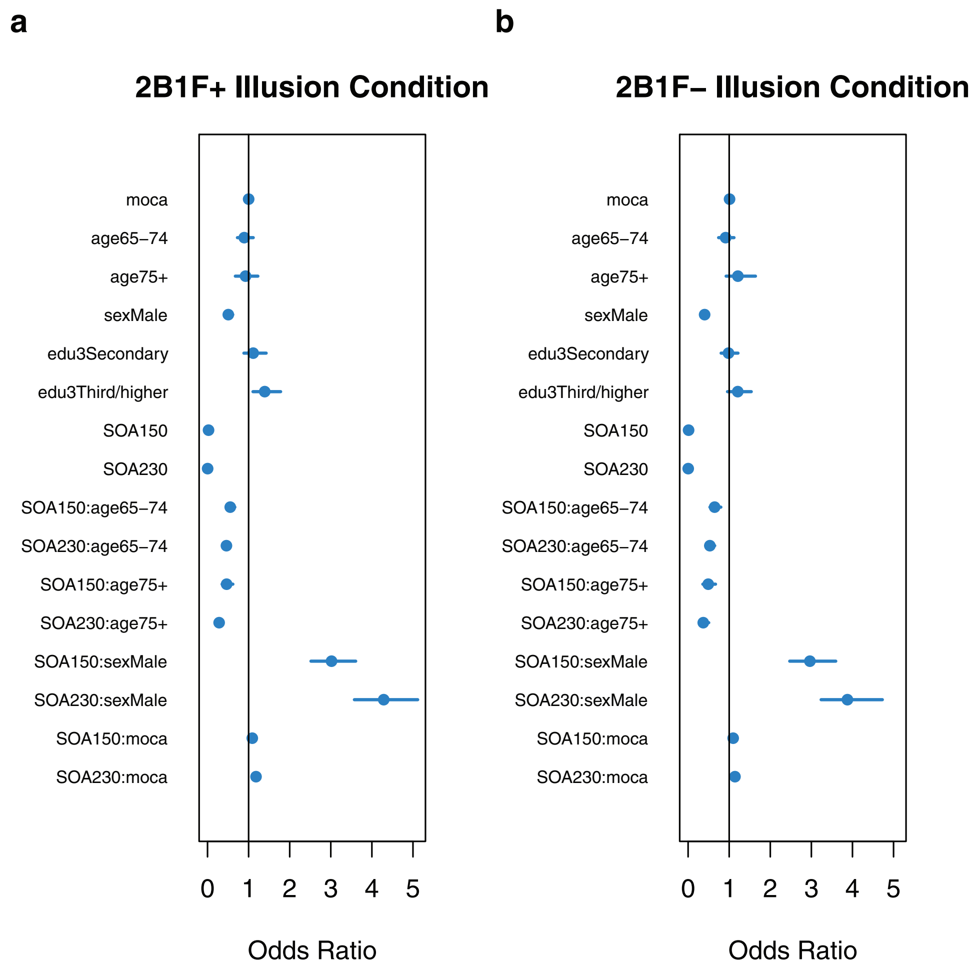

Figure 1. Odds ratio (95% credible intervals) for the two illusion conditions, 2B1F+ (left) and 2B1F– (right), in which a single beep either followed (AV-A) or preceded (A-AV) the bimodal (flash/beep) pair, respectively. moca = montreal cognitive assessment; SOA = stimulus onset asynchronies. See the online article for the color version of this figure.

We then assessed the role of age in susceptibility to the SIFI. Figure 1 shows that there was no effect for age at an SOA of 70 ms for either of the illusion conditions, as the 95% CIs for the age groups of 65 to 74 and 75 and older (compared with Ages 50–64 for an SOA of 70 ms) overlapped 1 in both the 2B1F+ and 2B1F– conditions (see also Table S.3 and Table S.4 of the online supplemental materials). There was, however, a significant effect for longer SOAs and age in the two illusion conditions: both older age groups (65 to 74 and over 75 years of age) were more susceptible to the illusion at longer SOAs of 150 ms and 230 ms compared with Ages 50 to 64 at an SOA of 70 ms (see Tables S.3 and S.4 of the online supplemental materials, and Figure 1). This result is consistent with previous findings (Setti, Burke, et al., 2011). Figure 2 shows the proportion of correct responses in the population by age and SOA. From Figures 2a and 2b, it can be seen that the proportion of respondents who correctly identified one flash for both illusion conditions was reasonably high across all age categories at an SOA of 70 ms, with between 62.7% and 66.4% correctly identifying one flash for the 2B1F+ condition and between 59.5% and 62% correctly identifying one flash for the 2B1F– condition at an SOA of 70 ms. We discuss this effect, likely because this SOA is too short a time period for the illusion to be registered; this is further discussed in the Discussion section. At longer SOAs, it can be seen that the proportion of respondents who correctly responded in at least one trial was much lower at the SOAs of 150 ms and 230 ms compared with 70 ms, and that there was also a large separation between age categories at longer SOAs, with a much higher proportion of younger respondents aged 50 to 64 responding correctly than those aged 65 to 74 or 75 and older (see also Figure 1 and Tables S.3 and S.4 of the online supplemental materials).

Global cognition was also found to significantly interact with SOA across both the illusion and control conditions, with a 1-point increase in participants' MoCA scores increasing the odds of a correct response by 1.1 at an SOA of 150 ms in both the 2B1F+ and 2B1F– conditions and by 1.2 and 1.1 at an SOA of 230 ms for the 2B1F+ and 2B1F– conditions, respectively (see Figure 3). MoCA was also positively related to the odds of correctly identifying two beeps and two flashes in the respective control condi-

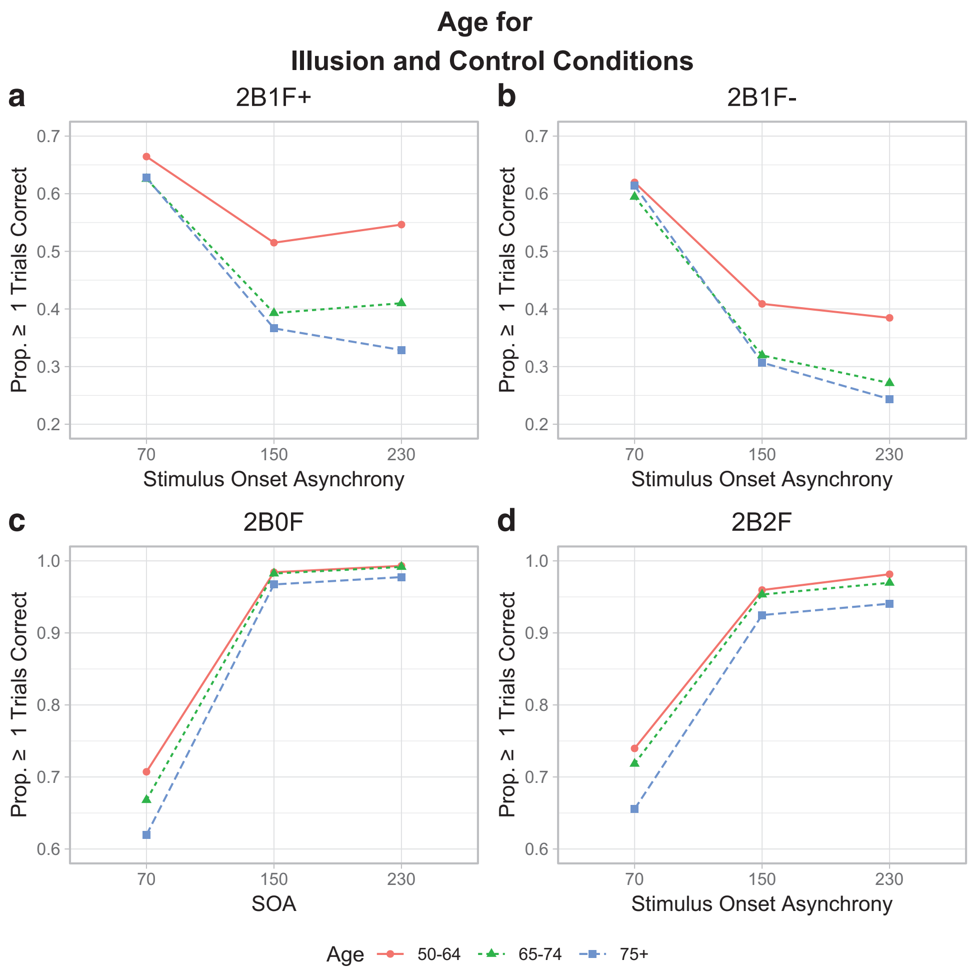

Figure 2. Proportion of participants answering one or both trials correctly across each age and stimulus onset asynchrony (SOA) category. Top panel shows results for the illusion conditions, 2B1F+ (left) and 2B1F– (right), in which a single beep either followed (AV-A) or preceded (A-AV) the bimodal (flash/beep) pair, respectively. Bottom panel shows results for the control conditions, 2B0F, with two beeps only (left), and 2B2F, which had two biomodal (flash/beep) pairs (right). See the online article for the color version of this figure.

tions (odds ratio 1.1 and 1.2 for SOAs of 150 ms and 230 ms for the 2B0F condition, and 1.1 for both the SOA of 150 ms and 230 ms for the 2B2F condition).

As for the sex of the participant, the results in Figure 4 show that males appear to be less susceptible to the illusion at longer SOAs than females, as indicated by the proportion of females responding correctly in the 2B1F+ condition, which is lower at longer SOAs than the proportion of male participants. The same occurs for the 2B1F– condition, although it is less pronounced and there are more females responding correctly than males with an SOA of 70 ms. These sex differences are statistically significant, as males had positive odds of being correct (odds ratio of 3.03 at 150 ms and 4.3 at 230 ms) to the 2B1F+ illusion condition (see Table S.3 and S.4 of the online supplemental materials) relative to females. The same overall trend was observed for the 2B1F– condition, although the effect was slightly smaller (odds ratio of 2.97 for an SOA of 150 ms and 3.91 at an SOA of 230 ms). In the control condition, 2B0F, males were more likely to be correct than females, with no interaction with SOA (see Figure S.1 of the online supplemental materials). Further analyses were conducted to also control for auditory processing and response time (processing speed) by including as predictor variables the correct responses to the two unisensory auditory beeps (2B0F condition at 70, 150, and 230 ms) or mean reaction time and reaction time variability over 100 trials of a two-choice reaction time task (results not shown). Controlling for these variables did not change the relationships between SIFI, age, MoCA, sex, and SOA reported in this study. This indicates that males are characterized by more efficient multisensory integration, as assessed by the SIFI, even when auditory temporal discrimination abilities are controlled for (2B0F).

Discussion

The present study tested the role of age, sex and global cognitive status (MoCA) in predicting multisensory perceptual function in a population-representative sample of 3,955 individuals aged 50 and

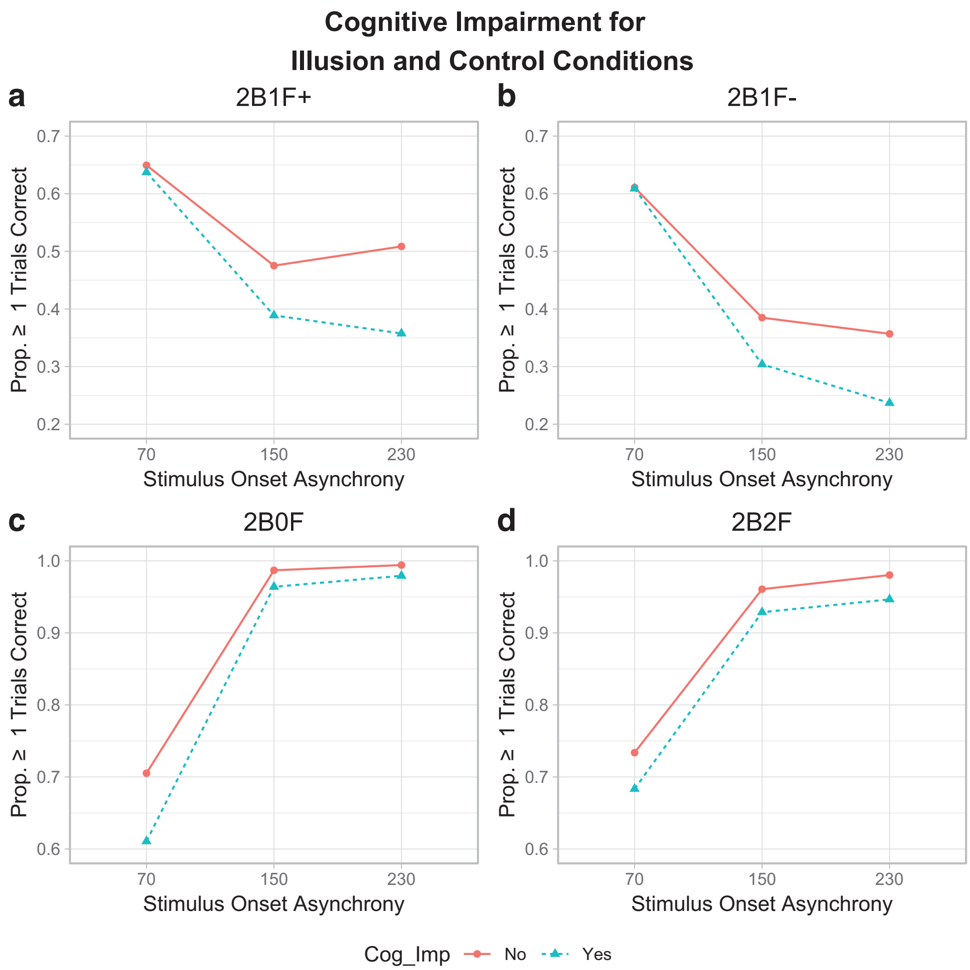

Figure 3. Proportion of correct responses for the illusion and control conditions in the SIFI for individuals scoring equal to or higher than 24 on the MoCA or lower (cognitive impairment). Top panel shows results for the illusion conditions, 2B1F+ (left) and 2B1F– (right), in which a single beep either followed (AV-A) or preceded (A-AV) the bimodal (flash/beep) pair, respectively. Bottom panel shows results for the control conditions, 2B0F, with two beeps only (left), and 2B2F, which had two biomodal (flash/beep) pairs (right). See the online article for the color version of this figure.

over. Here, we utilized the SIFI as a task of multisensory processing, which requires self-paced, categorical responses to the occurrence of unisensory or multisensory stimuli. The results on susceptibility to the SIFI are consistent with previous reports suggesting a role of ageing in multisensory perception and an overextended TBW.

The relationship between older adults' performance, as assessed with this task, and the results of previous reports suggesting multisensory enhancement in response times to multisensory stimuli (Bucur et al., 2005; Laurienti et al., 2006) remains to be established. A recent study directly testing the audiovisual TBW and multisensory enhancement in younger and older adults did not find a correlation between performance across the two tasks in the older population, suggesting separate underlying mechanisms (Basharat, Mahoney, & Barnett-Cowan, 2019). However, a discussion of the links between these processes is beyond the scope of the present work.

Our results suggest that participants aged between 65 and 74, and those over 75, are less correct than those aged between 50 and 64 at perceiving a single flash presented with two beeps at longer SOAs, indicating an association between age and multisensory integration, as captured by the SIFI assessment. These results confirm, in a large and heterogeneous sample of older adults, that audiovisual temporal integration allows for stimuli with large temporal asynchronies to be integrated, likely indicating less efficient integration with increasing age.

These results also revealed a novel, and important, finding that sex differences emerge in multisensory abilities: At longer SOAs, the performance of males was more correct than that of females, that is, males were less susceptible to the SIFI illusion. In contrast, females were more correct at identifying one flash at an SOA of 70 ms. The analyses on the auditory unisensory trials show that the greater susceptibility at longer SOAs in females is likely not due to differences in auditory processing, as controlling for correct per-

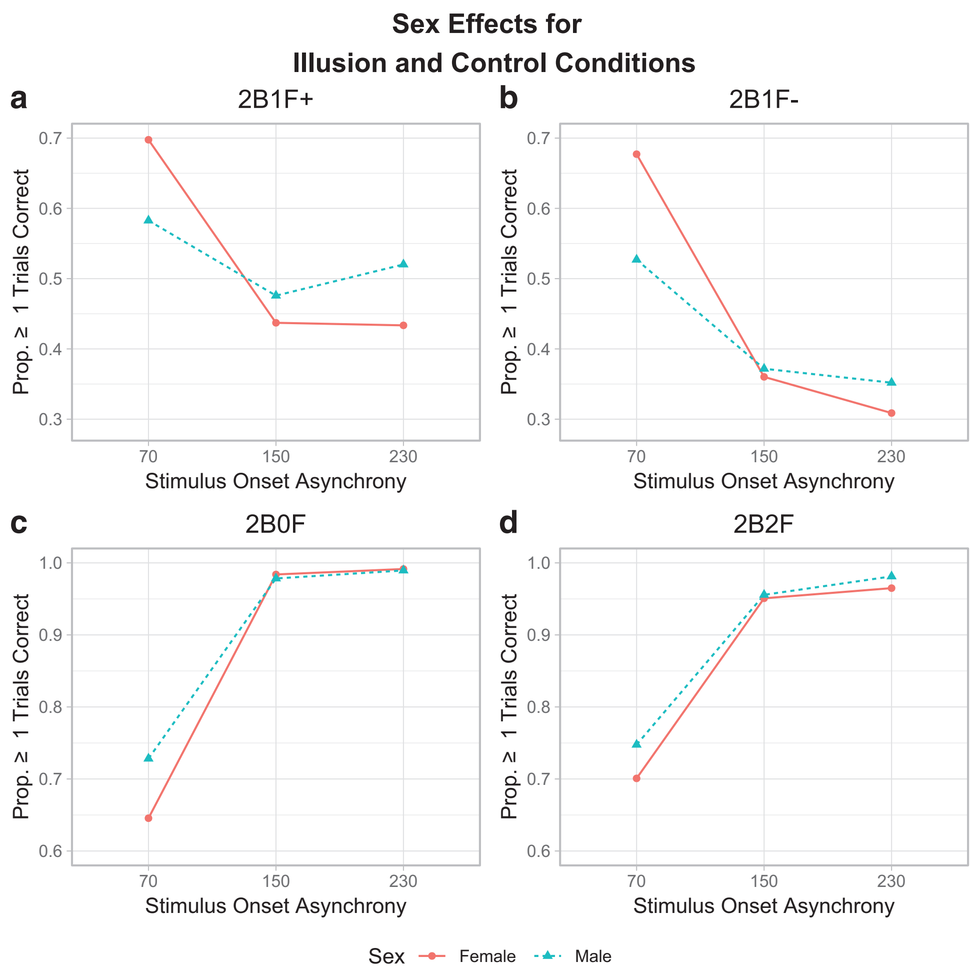

Figure 4. Proportion of male and female participants answering one or both trials correctly across each of the SOAs tested. Top panel shows results for the illusion conditions, 2B1F+ (left) and 2B1F– (right), in which a single beep either followed (AV-A) or preceded (A-AV) the bimodal (flash/beep) pair, respectively. Bottom panel shows results for the control conditions, 2B0F, with two beeps only (left), and 2B2F, which had two biomodal (flash/beep) pairs (right). See the online article for the color version of this figure.

ception of the two unisensory beeps did not affect the results. In addition, it is likely not due to the overall ability to discriminate two flashes as the model controls for this performance. Males were also more correct than females in the congruent multisensory condition; therefore, we argue that this result captures a genuine difference in multisensory processing between the sexes, which deserves further investigation. Although the exact cause behind this difference cannot be established here, one possibility is that a smaller TBW in males than in females might lead to different levels of susceptibility to the illusion, although it is unclear why females would be more correct with an SOA of 70 ms. The interindividual variability in TBW, especially in older individuals, is known to be large (Baum & Stevenson, 2017); therefore, it is not implausible that the TBW size could vary with sex. Another possibility is that perception in older females relies more on top-down predictions in responding to the audiovisual stimulation than in males. This is in line with previous findings on temporal segmentation and integration (Szelag, 1997), showing that females utilize more top-down strategies than men. However, both of these hypotheses remain speculative, and further experimental research is required to tease apart the possibilities. Nevertheless, to our knowledge, the role of sex in audiovisual temporal integration highlighted here is novel, and it has previously been overlooked in the literature.

A second important finding from our results relates to the association between cognitive function and multisensory integration. We found that participants with higher scores on the MoCA were less susceptible to illusions at long SOAs than individuals with lower MoCA scores. The MoCA is a tool for assessing global cognition and is generally considered a good screening tool for MCI. Our results therefore extend previous reports of an enlarged TBW in older people with MCI (J. S. Chan et al., 2015). However, performance on the MoCA is a predictor of both susceptibility to the illusion and ability to perceive two veridical flashes in the 2F2B congruent condition; therefore, it may also indicate a global effect of brain health on sensory processing, whereby individuals with poorer discrimination abilities at the perceptual level are also those who are older and have poorer cognitive performance overall (Lindenberger et al., 2011). The finding that multisensory integration could potentially be a screening tool for cognitive impairment, independently from its causative role, is important given that the SIFI is a very quick, language-free test to administer, which could be beneficial in certain clinical contexts. Although the mechanism underpinning a wider TBW in older individuals is largely unknown, changes in the TBW may be due to a decline in inhibitory function. Decline in inhibitory function may be associated with the TBW through lower inhibition of task-irrelevant stimuli from different modalities (Mozolic et al., 2011). In turn, decreased inhibition is related to decrease in the inhibitory neurotransmitter gamma-aminobutyric acid (GABA; Bedard & Barnett-Cowan, 2016). In turn, GABA dysfunction has been linked with the emergence of Alzheimer pathology, which starts with MCI symptomatology that converts into dementia. Although these causal links remain speculative, they may stimulate further research to elucidate the neural and behavioral underpinnings. The implications of these findings are particularly relevant for pathologies such as Parkinson's disease, which is linked with GABA dysfunction, manifest with sensory and motor deficits (Patel, Jankovic, & Hallett, 2014), and co-occurs with dementia (Aarsland, Andersen, Larsen, & Lolk, 2003). It is of note that the results are not due to general cognitive slowing, as they hold when controlling for performance in a simple two-choice response time task.

Some methodological considerations are necessary when comparing the present results with the results reported in the experimental literature. First, due to the time constraints of the TILDA health assessment, only two trials per condition were administered in the SIFI to each participant. In previous studies, a minimum of five to 10 trials were presented per condition. Therefore, as the SIFI is known to occur in a proportion of the total trials in both younger and older adults, the restricted number of trials per condition constitutes a limitation. If we consider previous experimental studies, individuals aged 65 and older report typically 40% to 60% correct responses when the SOA is 150 ms and 230 ms. In our sample, the proportion of trials in which the participant was susceptible to the illusion was higher, likely due to the TILDA sample being a population representative sample instead of a convenience sample. It is important to note that although the cross-sectional nature of the study also constitutes a limitation, as only SIFI data from Wave 3 of TILDA are available; the longitudinal design of the TILDA study will offer the opportunity to assess causal relationships between the links found and to determine whether the difference between the sexes changes with ageing. Wave 6 is planned for 2020; therefore, longitudinal data will be available in the near future.

Conclusions

In the context of the rapidly growing literature on multisensory perception, this is the first study offering the possibility to assess it in a large, representative sample of a population of older adults. We have shown that susceptibility to the SIFI increases with age, poorer global cognitive performance, and in females more so than males (at long SOAs). These novel findings extend our understanding of the basis of our cognition and, in particular, provide insight into how information from different modalities is integrated in the ageing brain.

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