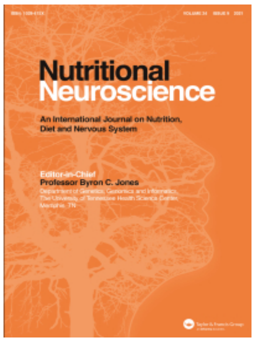

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Nutritional Neuroscience
An International Journal on Nutrition, Diet and Nervous System

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ynns20

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To cite this article: Alan O'Dowd, Deirdre M.A. O'Connor, Rebecca J. Hirst, Annalisa Setti, Rose Anne Kenny & Fiona N. Newell (2024) Nutrition is associated with differences in multisensory integration in healthy older adults, Nutritional Neuroscience, 27:11, 1226-1236, DOI: 10.1080/1028415X.2024.2316446

To link to this article: https://doi.org/10.1080/1028415X.2024.2316446

NUTRITIONAL NEUROSCIENCE
2024, VOL. 27, NO. 11, 1226–1236
https://doi.org/10.1080/1028415X.2024.2316446

Nutrition is associated with differences in multisensory integration in healthy older adults

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ABSTRACT

Diet can influence cognitive functioning in older adults and is a modifiable risk factor for cognitive decline. However, it is unknown if an association exists between diet and lower-level processes in the brain underpinning cognition, such as multisensory integration. We investigated whether temporal multisensory integration is associated with daily intake of fruit and vegetables (FV) or products high in fat/sugar/salt (FSS) in a large sample (N = 2,693) of older adults (mean age = 64.06 years, SD = 7.60; 56% female) from The Irish Longitudinal Study on Ageing (TILDA). Older adults completed a Food Frequency Questionnaire from which the total number of daily servings of FV and FSS items respectively was calculated. Older adults' susceptibility to the Sound Induced Flash Illusion (SIFI) measured the temporal precision of audio-visual integration, which included three audio-visual Stimulus Onset Asynchronies (SOAs): 70, 150 and 230 ms. Older adults who self-reported a higher daily consumption of FV were less susceptible to the SIFI at the longest versus shortest SOAs (i.e. increased temporal precision) compared to those reporting the lowest daily consumption ($p = .013$). In contrast, older adults reporting a higher daily consumption of FSS items were more susceptible to the SIFI at the longer versus shortest SOAs (i.e. reduced temporal precision) compared to those reporting the lowest daily consumption ($p < .001$). The temporal precision of multisensory integration is differentially associated with levels of daily consumption of FV versus products high in FSS, consistent with broader evidence that habitual diet is associated with brain health.

KEYWORDS
Ageing; audition; diet; multisensory; nutrition; perception; sound induced flash illusion; vision

Introduction

Diet is an important determinant of brain health in ageing. For example, increased consumption of fruit and vegetables (FV) is associated with healthier cognitive outcomes in older adults [1–3], possibly reflecting a positive influence of particular vitamins and minerals on brain health, including their capacity to reduce levels of inflammation [3–6]. Conversely, a diet high in fat/sugar/salt (FSS), partly characteristic of the so-called 'Western diet', is often associated with poorer cognitive health [7–10] and linked with increased inflammation that is detrimental to healthy brain functioning [10–13]. Dietary factors are also associated with sensory functioning, including eye health and the risk of age-related hearing loss [14,15], but it is unknown if diet is related to perceptual processes occurring in the brain such as multisensory integration. The ability to precisely combine incoming inputs from different sensory modalities is an important function of the brain and key to supporting higher-order cognitive [16] as well as physical [17] abilities. However, multisensory integration is vulnerable to the ageing process [18–21]. Research using the Sound Induced Flash Illusion, SIFI (a valid measure of temporal multisensory integration in which the temporal delay between a single 'flash' paired with two 'beeps' is systematically varied and the number of flashes perceived is reported [22]) has demonstrated that older adults typically integrate cross-sensory events separated over extended temporal intervals to a greater extent than their younger counterparts [18–21]. That is, the perception of a second illusory flash persists over longer audio-visual delays in older versus younger adults, as reported by a number of studies [see [18] for a review]. This is indicative of *less precise* multisensory function. That is, sensory inputs separated by relatively long delays should not

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Supplemental data for this article can be accessed https://doi.org/10.1080/1028415X.2024.2316446

be strongly integrated as they are less likely to pertain to a common event. The decline in the temporal precision of multisensory integration, while generally characteristic of ageing, is particularly pronounced in older adults with reduced cognitive [19,23,24] and/or physical [25,26] functioning. More specifically, in The Irish Longitudinal Study on Ageing (TILDA), a large-scale study of community-dwelling older adults resident in Ireland, increased illusion susceptibility at longer temporal delays is associated with reduced performance across a range of cognitive domains, including memory, verbal fluency and executive functions [19,24] and both slower gait speed [25] and lower grip strength [26], key indicators of frailty. Outside of this sample, increased illusion susceptibility at longer temporal delays is associated with mild cognitive impairment [23] and a history of falls [21] in older adults. This suggests that multisensory integration has potential as a biomarker of less healthy ageing, as less healthy older adults show wider temporal binding windows (TBW) for cross-sensory events.

Understanding whether there is a link between diet and multisensory integration is important, not only to expand upon our current understanding of the mechanisms linked with age-related changes in perceptual processes but also given that both diet and perceptual function are *modifiable* fixtures of daily living (e.g. [27]). Here, we examined the relationship between dietary habits, namely daily intake of FV versus items high in FSS, and the temporal precision of audio-visual integration using data obtained as part of TILDA [28]. Importantly, public health guidelines typically promote the consumption of multiple servings of FV on a daily basis and minimal intake of products high in FSS for older adults (e.g. [29]). In light of repeated evidence for an association between increased FV intake and improved brain health in contrast to increased FSS intake and reduced brain health, we hypothesised the following: (1) increased daily consumption of FV would be associated with more temporally precise patterns of multisensory integration (i.e. a narrower TBW) and (2) increased consumption of products characteristically high in FSS would be associated with less temporally precise patterns of multisensory integration (i.e. a wider TBW).

Methods

Participants

Participants were drawn from Wave 3 (2014–2015) of TILDA, a population representative sample of community-dwelling older adults, resident in Ireland [28]. The study was approved by the Trinity College Dublin Faculty of Health Sciences Research Ethics Committee on 9th June 2014 and complied with relevant data protection legislation. All participants provided informed consent at every testing wave. In total, 3,968 older adults aged fifty years or over had available data for the Sound Induced Flash Illusion (SIFI) experiment, which assessed temporal multisensory integration.

Sound induced flash illusion

Susceptibility to the SIFI [22] was included in a healthcare assessment at Wave 3 as a valid measure of the temporal precision of audio-visual integration [18]. In the SIFI, a single ‘flash’ is presented alongside two ‘beeps’. One of these beeps is temporally coincident with the flash while the other standalone beep is presented either before (pre condition) or after (post condition) this flash-beep pair. Typically, participants report perceiving a second, illusory flash in response to the presence of the standalone beep, indicating the capacity for audition to influence visual perception. In TILDA, the SIFI task was performed in the presence of a trained healthcare nurse. The participants vocally reported the number of perceived visual flashes and the nurse recorded these responses by pressing the corresponding number key on a laptop. Illusion trials (2B1F, where B = Beep and F = Flash) of the SIFI consisted of three audio-visual Stimulus Onset Asynchronies (SOAs), 70, 150 and 230 ms, where the standalone beep preceded (pre) or followed (post) the flash-beep pair across these varying delays. Due to time constraints within TILDA’s protocol, a total of twelve illusion trials were completed (i.e. two trials per SOA across pre–post conditions) in approximately six minutes. Further details of the SIFI protocol are available in Supplementary Materials.

Food frequency questionnaire

Older adults completed a Computer-Assisted Personalised Interview (CAPI), conducted by a trained interviewer in the home environment, followed by a Self-Completion Questionnaire (SCQ) which incorporated a Food Frequency Questionnaire (FFQ; see Supplementary Materials, Figure S1). The participants were asked to rate how often they consumed a serving of various food/drink items in the past year (‘Never/less than once a month’, ‘1-3 per month, ‘Once a week’, ‘2-4 per week’, ‘5-6 per week’, ‘Once a day’, ‘2-3 per day’, ‘4-5 per day’ and ‘6 + per day’). We extracted 25 food items, 6 items pertaining to FV and the remaining 19 items to products characteristically high in FSS as shown in Table 1, based on public health

Table 1. Outline of the food items from the Food Frequency Questionnaire (FFQ) included in each food category.

Food category	Food item
High in fat/sugar/salt	Butter (teaspoon), cream (tablespoon), salad dressings (tablespoon), packet vegetable soup, processed meats (including meat pies, pasties, sausage rolls, burgers, sausages), ham/bacon, chips/roast potatoes/potato products, sauces (tablespoon), Marmite/Bovril, plain biscuits, chocolate biscuits, confectionary (including sweets and chocolate bars), cakes/buns/desserts, jam/marmalade, savoury snacks (e.g. crisps/tortilla chips), cocoa/hot chocolate (cup), Ovaltine/Horlicks (cup), fizzy drinks (glass), fruit squash (glass).
Fruit and vegetables	Fresh/frozen/dried/tinned fruit, pure fruit juice (glass), green vegetables, yellow/orange vegetables, other/salad vegetables, vegetable soup (homemade/carton).

recommendations in the Republic of Ireland [29] and previous research involving data from the FFQ included in TILDA [30]. The FFQ data were converted to daily numerical values for servings of each food item and the total daily intake values for FV and, separately, items high in FSS were calculated.

The total daily FV servings consumed ranged from 0 to 12.6 (mean = 3.80, SD = 2.24) and the total daily servings of FSS items consumed ranged from 0 to 12.8 (mean = 3.85, SD = 2.31). Quintiles for total number of daily servings of FV and, separately, FSS items were derived using the 'quantcut()' function in R [31] via R Studio [32], as follows: **FV**, Q5 (mean = 1.37, SD = 0.46; 0–2; n = 539), Q4 (mean = 2.41, SD = 0.25; 2–2.85; n = 547), Q3 (mean = 3.31, SD = 0.29; 2.86–3.86; n = 545), Q2 (mean = 4.54, SD = 0.43; 3.86–5.42; n = 526), Q1 (mean = 7.40, SD = 1.72; 5.43–12.6; n = 536); **FSS**, Q5 (mean = 1.30, SD = 0.46; 0–1.97; n = 540), Q4 (mean = 2.41, SD = 0.27; 1.97–2.90; n = 538), Q3 (mean = 3.36, SD = 0.29; 2.90–3.91; n = 539), Q2 (mean = 4.63, SD = 0.47; 3.91–5.49; n = 537), Q1 (mean = 7.54, SD = 1.77; 5.49–12.8; n = 539). Further information on these quintiles is provided in Supplementary Materials (Figures S2, S3 and S4; Tables S2, S3 and S4).

Analysis

Response accuracy to illusion trials of the SIFI, the principal outcome of this study, took the form of 0 (i.e. an incorrect response on both trials, indicating consistent 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 [33]. The following terms were included in the main model: age, stimulus onset asynchrony (SOA; 70, 150, 230 ms), participant 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+; angina, heart attack, diabetes/high blood sugar, stroke, mini-stroke/TIA, high cholesterol, heart murmur, abnormal heart rhythm, seated hypertension) and non-cardiac (0, 1, 2+; chronic lung disease, asthma, arthritis, osteoporosis, cancer, Parkinson's disease) diseases, depression (CES-D $\geq$ 9), waist-to-hip ratio (WHR), current living environment (CLE: rural, urban other, Dublin), weekly physical activity level (metabolic minutes a week, METs, based on the International Physical Activity Questionnaire-Short Form, IPAQ), global cognition (MoCA score), current smoker status (non-smoker, former smoker, current smoker), alcohol consumption (CAGE questionnaire for problematic alcohol consumption; yes, no, missing), FV quintile (5^{th}, 4^{th}, 3^{rd}, 2^{nd}, 1^{st}), FSS quintile (5^{th}, 4^{th}, 3^{rd}, 2^{nd}, 1^{st}), 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. The analysis model also included SOA*age, SOA*sex, SOA*MoCA, SOA*CLE, SOA*WHR, SOA*FV and SOA*FSS interaction terms and a random intercept term (for participant ID). All continuous variables were scaled prior to analysis.

To address our hypotheses, the statistical significance of the SOA*FV and SOA*FSS interaction terms was determined via likelihood ratio tests, where we evaluated the fit of the model with and without each interaction term respectively while holding constant all of the aforementioned model terms. The inclusion of both SOA*FV and SOA*FSS interaction terms allowed us to assess the independent contribution of total daily consumption of each food group on SIFI performance while controlling for total daily intake of items in the opposite food group. As we conducted two likelihood ratio tests in total, the alpha level for statistical significance was adjusted using the Bonferroni correction to $\alpha = .025$. The analysis was conducted with R [31] in R studio [32].

Results

Data were omitted prior to analysis for participants who met the following criteria: they were registered as legally blind (n = 2), had a suspected mild cognitive impairment (MCI) (based on a Montreal Cognitive Assessment Score < 23; n = 456; as MCI is associated with less precise temporal audio-visual integration

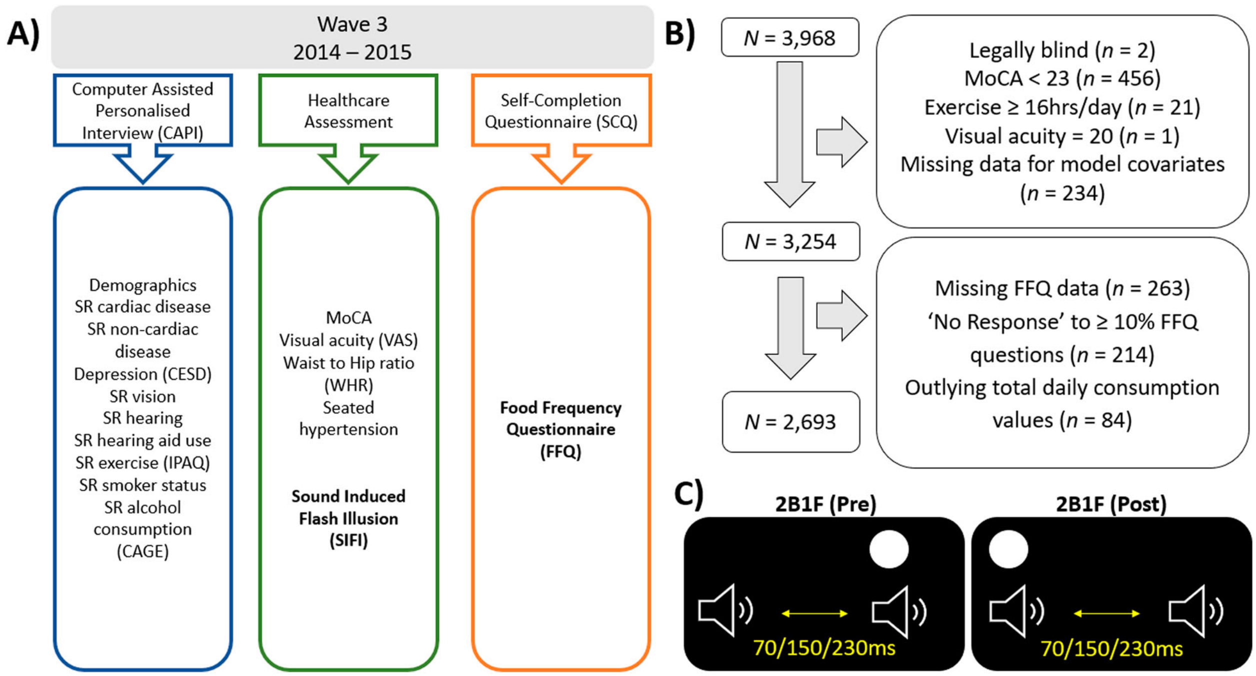

Figure 1. An illustration of the testing protocol for Wave 3 of TILDA. **A)** A schematic summary of the variables included in the present study. SR = self-reported. IPAQ = International Physical Activity Questionnaire. CAGE = CAGE questionnaire for problematic drinking. MoCA = Montreal Cognitive Assessment. Seated hypertension = average resting seated SBP ≥ 140 and/or DBP ≥ 90 mm/Hg. SR cardiac disease includes self-reported clinical diagnosis of stroke, ministroke, heart attack, heart murmur, abnormal heart rhythm, angina, high cholesterol and/or diabetes/high blood sugar. SR non-cardiac disease includes self-report clinical diagnosis of Parkinson's Disease, chronic lung disease, asthma, arthritis, osteoporosis and/or cancer. **B)** A schematic summary of the sampling exclusion criteria. **C)** A visual representation of the Sound Induced Flash Illusion (2B1F), where B = 'beep' and F = 'flash'. Pre refers to the standalone beep preceding the flash-beep pair and post refers to the standalone beep following the flash-beep pair.

[23]) and/or had missing or spurious data for important model covariates (n = 256). Data from participants who did not partake in the FFQ (n = 263), who reported total daily FV or FSS intakes greater than 3 standard deviations above or below the group mean (n = 84) and/or who were marked as having 'No Response' for 10% or more of these food items (i.e. 3 or more missing lines; n = 214) were also omitted prior to analysis. For the remainder, it was assumed that 'No Response' equated to no consumption of that item. This resulted in a final sample of 2,693 older adults (mean age = 64.06 years, SD = 7.60; 56% female, see Figure 1 and Supplementary Materials, Table S1).

Fruit and vegetables

A likelihood ratio test revealed that the SOA*FV interaction term significantly contributed to the model predicting accuracy on the illusion trials of the SIFI ($\chi^2_{(8)}$ = 19.34, p = .013). Compared to older adults in the 5th quintile (i.e. the lowest FV consumption group), **(1)** older adults in the 1st quintile had 38% higher odds of making an accurate response at 230 ms (odds ratio, OR = 1.38, 95% CI [1.07,1.78]), relative to 70 ms, **(2)** older adults in the 2nd quintile had 45% higher odds of making an accurate response at 150 ms (OR = 1.45, 95% CI [1.13,1.86]) and 64% higher odds of making an accurate response at 230 ms (OR = 1.64, 95% CI [1.28,2.10]) relative to 70 ms, **(3)** older adults in the 3rd quintile had 29% higher odds of making an accurate response at 230 ms (OR = 1.29, 95% CI [1.01,1.66]), relative to 70 ms and **(4)** older adults in the 4th quintile had 30% higher odds of making an accurate response at 230 ms (OR = 1.30, 95% CI [1.02,1.66]), relative to 70 ms. Full model results are available in Supplementary Materials, Table S5. Predicted accuracy values across SOAs per FV quintile are shown in Figure 2 and Table 2.

Fat/sugar/salt

The SOA*FSS interaction term significantly contributed to the model predicting accuracy on the illusion trials of the SIFI ($\chi^2_{(8)}$ = 27.66, p < .001). Compared to older adults in the 5th quintile (i.e. lowest consumption of FSS), **(1)** older adults in the 1st quintile had 29% lower odds of making an accurate response at 150 ms

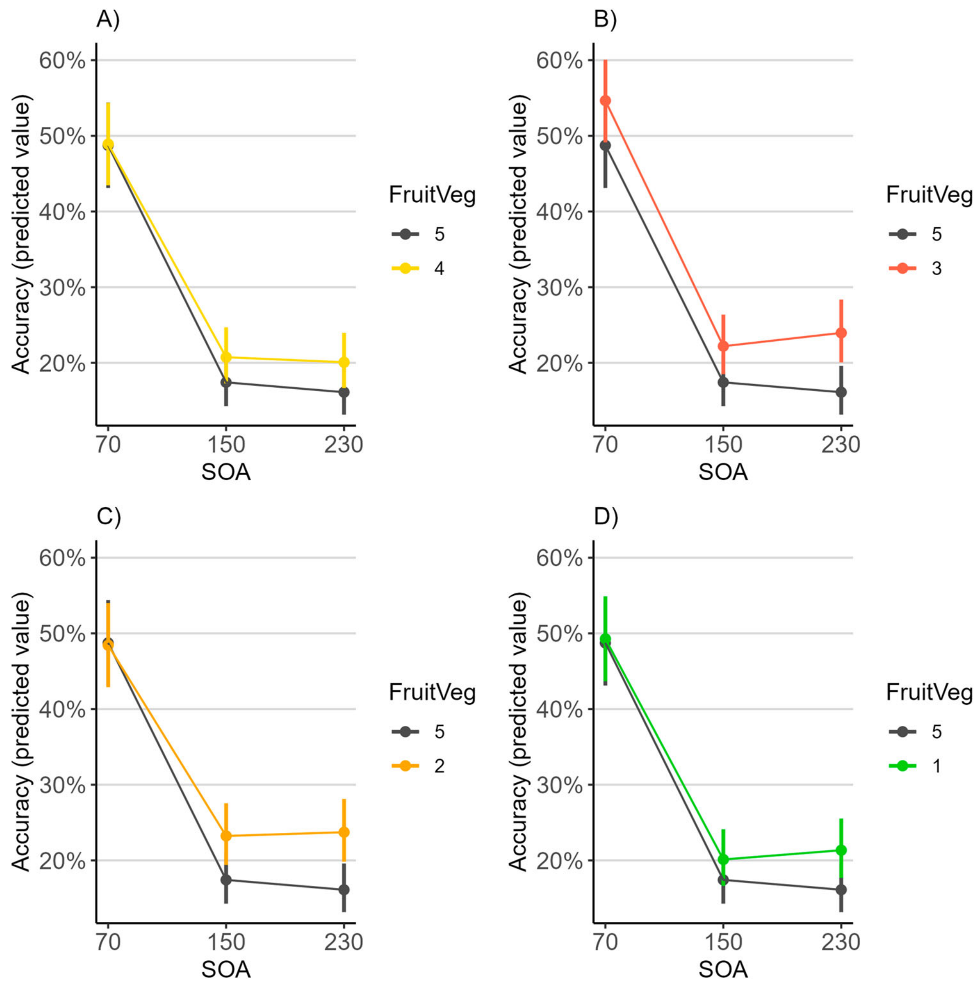

Figure 2. The predicted accuracy values on the illusion (2B1F) trials of the SIFI for (A) the 5th and 4th quintiles, (B) the 5th and 3rd quintiles, (C) the 5th and 2nd quintiles and (D) the 5th and 1st quintiles of total daily fruit and vegetable (FruitVeg) intake. Higher values indicate increased accuracy for identifying the number of flashes presented (whilst ignoring the beeps), therefore reduced susceptibility to the illusion. Error bars indicate 95% confidence intervals.

(OR = 0.71, 95% CI [0.56,0.91]) and 36% lower odds of making an accurate response at 230 ms (OR = 0.64, 95% CI [0.50,0.82]), relative to 70 ms, **(2)** older adults in the 2nd quintile had 30% lower odds of making an accurate response at 150 ms (OR = 0.70, 95% CI [0.55,0.89]) and 38% lower odds of making an accurate response at 230 ms (OR = 0.62, 95% CI [0.49,0.79]), relative to 70 ms, and **(3)** older adults in the 4th quintile had 34% lower odds of making an accurate response at 150 ms (OR = 0.66, 95% CI [0.52,0.84]) and 22% lower of odds of making an accurate response at 230 ms (OR = 0.78, 95% CI [0.61, 0.99]) relative to 70 ms. Full model results are available in Supplementary Materials, Table S5. Predicted accuracy values across SOAs per FSS quintile are shown in Figure 3 and Table 3.

Table 2. Table shows the predicted values for accuracy [95% confidence intervals] across stimulus onset asynchronies (SOA; 70, 150, 230 ms) for each quintile (Q) of average daily fruit and vegetable intake.

	70 ms	150 ms	230 ms	70 v 150	70 v 230
Q1	49% [44,55]	20% [17,24]	21% [18,26]	29%	28%
Q2	48% [43,54]	23% [19,28]	24% [20,28]	25%	24%
Q3	55% [49,60]	22% [19,26]	24% [20,28]	33%	31%
Q4	49% [43,54]	21% [17,25]	20% [17,24]	28%	29%
Q5	49% [43,54]	17% [14,21]	16% [13,20]	32%	33%

Table 3. Table shows the predicted values for accuracy [95% confidence intervals] across stimulus onset asynchronies (SOA; 70, 150, 230 ms) for each quintile (Q) of total daily intake of items high in fat/sugar/salt.

	70 ms	150 ms	230 ms	70 v 150	70 v 230
Q1	51% [45,56]	20% [17,24]	19% [15,22]	31%	32%
Q2	52% [47,58]	20% [17,24]	19% [16,23]	32%	33%
Q3	50% [45,56]	22% [18,26]	23% [19,27]	28%	27%
Q4	48% [43,54]	17% [14,21]	20% [17,24]	31%	28%
Q5	48% [43,54]	24% [20,28]	24% [21,29]	24%	24%

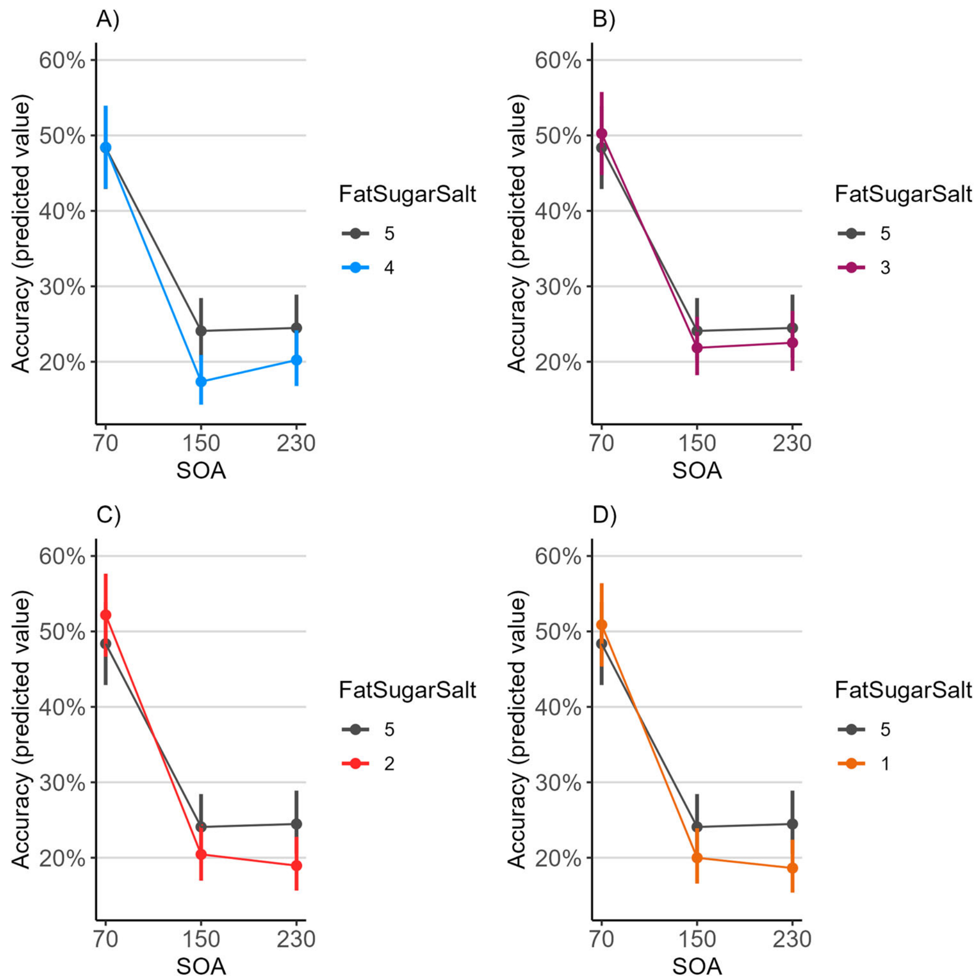

Figure 3. The predicted accuracy values on the illusion (2B1F) trials of the SIFI for (A) the 5th and 4th quintiles, (B) the 5th and 3rd quintiles, (C) the 5th and 2nd quintiles and (D) the 5th and 1st quintiles of total daily intake of items high in fat/sugar/salt. Higher values indicate increased accuracy for identifying the number of flashes presented (whilst ignoring the beeps), therefore reduced susceptibility to the illusion. Error bars indicate 95% confidence intervals.

Discussion

We examined the association between the temporal precision of multisensory integration and the daily consumption of fruit and vegetables (FV) and, separately, items characteristically high in fat/sugar/salt (FSS) in a large sample of older adults (N = 2,693) who partook in The Irish Longitudinal Study on Ageing (TILDA [28]). In line with our hypotheses, our results showed that older adults who consumed a greater number of daily servings of FV, based on self-reported dietary habits, were less susceptible to the Sound Induced Flash Illusion (SIFI [22]) at the longest versus shortest audio-visual offsets compared to older adults who consumed the fewest daily FV servings, suggesting *more temporally precise* multisensory integration. Conversely, older adults who reported consuming a greater number of daily servings of food items high in FSS were more susceptible to the SIFI at the longer versus shortest audio-visual offsets compared to older adults who consumed the fewest daily servings of FSS items, suggesting *less temporally precise* multisensory integration. These results emerged when controlling for important factors, including age, waist-to-hip ratio, cardiovascular health, sensory function and global cognition.

Our results align well with broader evidence that diet is an important determinant of health outcomes in ageing; that is, an increased consumption of FV can be beneficial for brain function in older adults [1–6] while an increased consumption of FSS has deleterious effects for cognitive health [7–13]. Multisensory integration is a relatively lower-level process occurring in the brain relative to the domains of cognitive functioning previously associated with diet in ageing populations [1–13]. Multisensory integration has been described as a ‘scaffold’ that is critical to high-level cognition [16] and, as stated above, less healthy cognitive function is associated with temporally less precise patterns of multisensory integration [19,23,24]. Therefore, dietary factors appear to be associated with not only high-level cognitive processes in the brain [1–13] in addition to sensory health [14,15] but also the precision by which sensory inputs are integrated, a process which fundamentally supports broader cognitive and physical functioning [16,17]. Therefore, these novel findings further reinforce the importance of public health campaigns that seek to promote healthy dietary practices, including limiting FSS and increasing FV intake in the daily diet (e.g. [29]).

The exact mechanisms underpinning the present findings are unclear, given the appreciable complexity in the relationship between diet/nutrition and brain function. It is not possible to extract specific macro- or micronutrient consumption data from the FFQ used in TILDA; however, as nutrients and vitamins often interact to give rise to complex effects of diet on health, such an approach may be too restrictive. Indeed, FV are good sources of several vitamins, minerals and other compounds (e.g. flavonoids, fibre) that have been associated with improved cognitive outcomes in ageing, including a reduced risk of cognitive decline [1–6]. Interestingly, low levels of folate, which is sourced mainly from leafy green vegetables, are predictive of accelerated cognitive decline in TILDA [6]. Folate levels were not assessed at Wave 3, when SIFI was introduced into TILDA. Given that other studies of ageing have similarly reported links between folate and cognitive outcomes (e.g. [34]), this would be a fruitful area of research for future studies investigating the links between perception and nutrition.

Physiologically, dietary factors, such as general adherence to 'healthy' (e.g. Mediterranean) versus 'unhealthy' (e.g. Western) diets (as well as intake of specific macro- and micronutrients), can influence the structural and functional characteristics of the brain, including grey matter volume and patterns of functional connectivity across multiple brain regions (see [35] for a review). FV are high in antioxidants and this may help to mitigate the level of age-related oxidative stress occurring in the brain [36,37], a process associated with systemic neuroinflammation, neural dysfunction/necrosis and cognitive decline. Conversely, an increased intake of FSS may contribute to oxidative stress, promote inflammatory responses, subdue the expression of brain-derived neurotrophic factor and adversely impact upon the blood brain barrier (e.g. [10–13]); these processes, particularly neuroinflammation, may serve as plausible biological mechanisms underpinning the association between diet and less precise multisensory integration, although further empirical research is needed in this regard. For example, less precise temporal multisensory integration is evidenced in obesity, which may be related to sustained, ongoing pro-inflammatory processes in the body [38]. Obesity is linked with many of the same physiological changes that accompany poor dietary practices as well as an elevated risk of poor cognitive outcomes [10]. As our models controlled for waist-to-hip ratio, our findings cannot be fully explained by diet-related differences in participant weight. Moreover, supplementary analyses indicated that neither FV nor FSS quintiles were statistically significantly associated with levels of C-reactive protein (CRP), a sensitive marker of ongoing inflammation that has been associated with nutritional factors [39] (see Supplementary Materials for full results).

Diet can also influence the neurotransmitter gamma-aminobutyric acid, GABA, which is involved in inhibitory processes and is known to be adversely impacted by the healthy ageing process [40,41]. The inhibitory function of GABA may be important for the ability to effectively inhibit irrelevant information and it has been suggested that a decline in GABA levels might facilitate changes in multisensory integration [19]. Indeed, GABA levels in the superior temporal sulcus are positively associated with the degree of susceptibility to the SIFI, (albeit at a short audio-visual offset only) [42]. As such, it is possible that healthy versus unhealthy dietary habits may be related to the temporal precision of multisensory integration through their differential effects on the concentration of GABA within the older adult brain. Finally, dietary habits can shape the gut microbiome, which is important as the microbiome is associated with brain health via the microbiota-gut-brain axis [12,13,43,44]. For example, the presence of particular families of bacteria in the gut or greater overall microbiome diversity can be associated with improved cognitive performance in older adult populations (e.g. [45,46]). Mechanistically, this may reflect an influence of the microbiome on neuroinflammatory processes (e.g. [12]). GABA concentrations in the central nervous system can also be influenced by the composition of the microbiome, as particular types of bacteria can contribute to GABA production [47]. As such, the link between cognition and nutrition may be mediated by the health of the microbiome which impacts upon the functioning of the brain. Whether this relationship extends to perceptual function is unclear, but future empirical research could examine this association in greater detail by directly analysing the composition of the microbiome of older adults.

To our knowledge, this is the first study to investigate the link between dietary factors specifically and temporal multisensory integration in older adults and our findings are important given that less precise multisensory integration appears to be a largely maladaptive characteristic of the ageing process, associated with less healthy cognitive and/or physical functioning [18–21,23–26]. However, additional studies are needed to establish the potential of SIFI susceptibility as a reliable, standalone predictor of broader health trajectories in ageing. Interestingly, multisensory integration can be modified with training, using relatively cost-effective methods that are accessible to an older adult population [27,48,49]. Importantly, diet is also modifiable. As such, any association between particular dietary habits and imprecise patterns of multisensory integration may be addressed and potentially rectified via nutritional and/or perceptual modifications. Moreover, targeted perceptual training combined with healthy lifestyle practices could promote positive neuroplastic changes in the ageing brain [50], potentially mitigating the loss of precision in multisensory integration that typically occurs during the ageing process, thus promoting wider health benefits [18–21,50]. Indeed, the neural benefits of a healthy diet [50] and, separately, multisensory learning [51] have been generally documented. Nonetheless, while our results suggest that maintaining a healthy diet is associated with improved precision of multisensory integration, further empirical research (ideally incorporating longitudinal data and/or direct dietary modifications) is required to clarify the nature of this relationship, in particular the potential for causality and its physiological substrates.

There are also limitations to this study. To begin with, we acknowledge that the TILDA sample is relatively healthy and consists only of community-dwelling older adults resident in Ireland. This limits the generalisability of our findings to other older adult cohorts. For example, the extent to which the association between nutrition and multisensory integration is observable in less heathy older adults is uncertain, given that their nutritional profiles may be different to those of healthier populations and multisensory integration is associated with cognitive and physical health profiles more broadly. We also cannot establish relationships between SIFI susceptibility and levels of specific vitamins, minerals or other substances in TILDA. We acknowledge that the FFQ is not exhaustive and the lack of specificity regarding the individual items consumed within certain food groups (e.g. FV) is not ideal, particularly given that dietary diversity and variety is important (e.g. [52,53]). Moreover, while our approach allowed us to examine the role of specific dietary elements on perceptual processes that are known to be associated with different cognitive and physical profiles in ageing, we acknowledge that we have focused on the association between multisensory integration and two specific food groups only. Finally, we recognise that there are limitations in the SIFI paradigm utilised in TILDA, namely its administration at only one wave of TILDA and the relatively low number of trials and SOAs. This was due to practical constraints as the SIFI was embedded in a long and comprehensive health assessment, thereby limiting the time available for the experiment to just six minutes. Additional research, expanding upon the present paradigm, would help to capture with greater precision how consumption patterns shape temporal multisensory integration in healthy ageing. We also recognise that the SIFI was the sole measure of multisensory integration administered once only in TILDA. Although SIFI is a well validated paradigm and has been shown repeatedly to be sensitive to the ageing process [18–21], a more comprehensive battery of perceptual tests, ideally administered in a longitudinal assessment, is needed to clarify whether the observed association between nutritional patterns and multisensory integration is specific to the *temporal* characteristics of multisensory integration or significantly broader in scope.

Conclusions

The cognitive health of an older adult can be determined by multiple factors, including the composition of his/her diet. Here, we found that community-dwelling older adults (N = 2,693) who reported consuming more daily servings of FV were less susceptible to the SIFI at the longer versus shortest SOAs compared to those who consumed the fewest daily servings. In general, older adults who reported consuming more daily servings of items high in FSS were more susceptible to the SIFI at the longer versus shortest SOAs compared to those who consumed the fewest daily servings of these items. These effects emerged when controlling for important factors such as cardiovascular health, exercise levels, sensory function, waist-to-hip ratio and global cognition. These novel findings suggest that diet is linked with the precision by which the brain combines cross-sensory inputs in time, therefore reinforcing the value of ongoing public health efforts promoting adherence to healthy dietary practices in the general population.

Author contributions

The Irish Longitudinal Study on Ageing (TILDA) is coordinated 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.

Data and code availability

To acquire access to the data from The Irish Longitudinal Study on Ageing (TILDA), see https://tilda.tcd.ie/data/accessing-data/. Data from the Sound Induced Flash Illusion are available in the publicly released dataset which can be accessed via a hotdesk facility or by requesting access through the Irish Social Science Data Archive or the Interuniversity Consortium for Political and Social Research. Information on how to access these data as well as direct links to the request forms can be found at https://tilda.tcd.ie/data/accessing-data/ and https://tilda.tcd.ie/data/accessing-data/hotdesk/. The complete R script with analysis code is publicly available on the Open Science Framework at https://osf.io/me34r/?view_only = 5e1db342831f41d28b69df45f5a2918b.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Health Research Board: [grant nos ILP-PHR-2017-014].

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