



Special Issue “Multisensory integration”: Research Report

The effect of eye disease, cataract surgery and hearing aid use on multisensory integration in ageing



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ARTICLE INFO

Article history:

Received 17 February 2020

Reviewed 1 Jun 2020

Revised 10 July 2020

Accepted 26 August 2020

Published online 8 October 2020

Keywords:

Sound-induced flash illusion

Multisensory

Ageing

Eye disease

Hearing aids

ABSTRACT

Sensory impairment is common in ageing, as are approaches to treat it. However, the impact of age-related sensory impairment upon multisensory perception remains unexplored, despite the multisensory nature of our environment. Here, we used data from The Irish Longitudinal Study of Ageing (TILDA) to investigate whether common, age-related eye diseases (cataracts, glaucoma and Age-Related Macular Degeneration, ARMD) and clinical intervention to improve sensory function (cataract removal and hearing aids) influence multisensory integration in older adults. Integration was measured using the Sound-Induced Flash Illusion (SIFI), and the extent to which identifying two flashes was improved by accompanying auditory information (“visual gain”). Visual gain was not influenced by eye disease or treatment. For the SIFI, participants self-reporting cataracts, ARMD or glaucoma were as susceptible as healthy controls, even when controlling for age, sex, cognition, self-reported vision/hearing and visual acuity. In a second analysis using retinal photographs, glaucoma and ARMD (hard drusen) did not influence susceptibility relative to controls. However, participants with soft drusen ARMD were more susceptible to the illusion at long Stimulus-Onset Asynchronies (SOAs) compared with controls. Following this, we identified groups reporting bilateral cataract removal or hearing aid acquisition >4 years and <2 years prior to assessment, enabling comparison of longer- and shorter-term effects of interventions. Cataract removal groups did not differ from controls. Longer-term hearing aid users were less susceptible to the SIFI at short SOAs compared with controls. Our findings suggest that multisensory integration in ageing might be specifically influenced by ARMD (soft drusen) and hearing aid use.

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<https://doi.org/10.1016/j.cortex.2020.08.030>

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1. Introduction

Imagine you are crossing a road. As you approach the edge of the pavement you perform a ritual that you have performed from a very young age; stop, look and listen. In this situation, you use information from multiple senses to increase the likelihood of detecting an important event in the environment, an oncoming vehicle. A myriad of experimental evidence shows that presenting congruent information to multiple modalities conveys a significant perceptual advantage, facilitating detection (Lovelace et al., 2003), identification (Chen & Spence, 2011) and response times (Gondan et al., 2005; Harrison et al., 2010; Miller, 1982) towards target stimuli. Furthermore, due to the properties of multisensory neurones, the advantage to be gained from multisensory input can be even greater when the information available to each sense is weak, a principle known as inverse effectiveness (Meredith & Stein, 1983; Stanford & Stein, 2007; Stein & Stanford, 2008; but see; Holmes, 2009). As such, if you are crossing the road on a foggy day, using multiple senses may be even more advantageous for perceiving a safe time to cross. In a similar manner, the relative benefit from multisensory integration might be even greater in individuals who experience degraded input in one or more sensory systems, for example through age-related sensory decline and eye disease.

The goal of the current study was to assess whether multisensory integration in older adults is influenced by common age-related eye diseases (cataracts, glaucoma and Age-Related Macular Degeneration; ARMD) and clinical interventions to improve sensory function (cataract removal and hearing aid use) using data from The Irish Longitudinal Study on Ageing (TILDA). Assessing the impact of sensory function and clinical interventions is highly important, given the ubiquitous nature of ocular pathologies and corrective procedures for both vision and hearing in the older adult population. Furthermore, whilst several lines of evidence suggest that the relative increase in sensory integration in ageing (discussed below) may serve a compensatory purpose for perception (de Boer-Schellekens & Vroomen, 2014; de Dieuleveult et al., 2017), other evidence suggests that possible “over integration” might have adverse consequences, as it is associated with fall risk (Setti et al., 2011), mild cognitive impairment (Chan et al., 2015), and poorer global cognitive scores (Hernández et al., 2019). It is therefore essential to understand whether impaired sensory function in ageing impacts multisensory integration, leading to suboptimal multisensory processing with possible clinical risk and, furthermore, establish whether clinical interventions to improve sensory function may promote multisensory integration to age-normal levels (Gieseler et al., 2018).

The primary measure of multisensory integration in the TILDA study is known as the Sound-Induced Flash Illusion (SIFI). In this illusion, presenting a single visual ‘flash’ with

two successive auditory ‘beeps’ results in the illusory percept of two flashes (Shams et al., 2000; for reviews see; Hirst et al., 2020; Keil, 2020). In the current study, we refer to the SIFI as a measure of perceptual rather than sensory function. This is because the SIFI represents the final experienced percept of the individual, once senses have been combined in the brain, rather than the function of peripheral sensory receptors. Nevertheless, sensory function can impact on perception through changes in the quality of the signals to be combined.

Perception in the SIFI is influenced by the reliability of information from each modality. For example, Shams et al. (2005) found that the SIFI was strongest when the accuracy for judging the presence of two beeps was higher than the accuracy for judging two flashes. In other words, if auditory information is more reliable for judgements of events than vision, audiovisual perception is biased towards the information in the auditory modality. SIFI susceptibility therefore reflects a measure of multisensory integration in which perception is influenced by the relative reliability between vision and hearing. In line with this, recent evidence has shown that susceptibility to the SIFI in the TILDA cohort is mediated, although not fully accounted for, by unisensory reliability in ageing (Hirst et al., 2019). The SIFI should therefore be stronger in those who have less reliable vision (i.e., due to eye disease) although susceptibility might be shifted towards age-normal levels through corrective procedures (such as cataract removal).

In general, multisensory integration is thought to increase in ageing (de Dieuleveult et al., 2017; Freiherr et al., 2013; Laurienti et al., 2006). However, it is also important to understand how the pattern of integration changes with age. The SIFI can be used to measure age-related change in the width of the Temporal Binding Window (TBW), which reflects the sensitivity of the perceptual brain to temporal synchrony. That is, when faced with two signals, integration is most beneficial if these signals originate from a common source. One way of determining this is if signals occur close in time. For example, when following a conversation we expect the lip movements of our companion and the speech sounds they produce to occur close in time, whilst sounds originating from other sources might be asynchronous to lip movements (see Venezia et al. (2016) for details on audio-visual timing in speech perception). Following this, it can be considered optimal to integrate signals occurring close, or synchronously, in time. In relation to the SIFI, susceptibility to the illusion occurs when the first flash-beep pair and second beep are presented within a short Stimulus Onset Asynchrony (SOA) but susceptibility typically decreases at longer SOAs. In young adults, SOAs greater than 70–100 msec reduce the illusion (Shams et al., 2000), consistent with the proposed temporal properties of multisensory neurones (Meredith et al., 1987). However, in older adults, the illusion persists at SOAs longer than 200 msec, reflecting an age-related widening, and

arguably reduced efficiency, of the TBW (McGovern et al., 2014; Setti et al., 2011). In this study we therefore identify whether eye disease and clinical interventions (cataract removal and hearing aid use) impact the pattern of SIFI susceptibility from short to long SOAs.

A second measure of integration we focus on is the ability to utilise auditory information to benefit visual judgements. We term this benefit “visual gain”. It is possible that increased integration in ageing serves to compensate for unisensory decline. In a systematic review of multisensory integration in ageing in 20 studies, the benefit of multisensory stimuli was greater in older compared with younger adults (de Dieuleveult et al., 2017). In the current study, we assess whether benefits for multisensory integration are greater in individuals with eye disease, through comparing unimodal and crossmodal congruent conditions in the SIFI. We would expect that accuracy for judging two flashes should be higher when two flashes are also simultaneously presented with two beeps. Furthermore, we might expect this difference to be greater in those with visual impairment.

Despite the prevalence of sensory impairments, to our knowledge no study has investigated the effect of eye disease on the SIFI in an older adult population, despite clear predictions that this should alter sensory weighting during integration (Garcia et al., 2017; Hirst et al., 2019). Studies with younger adults have investigated the effect of amblyopia (Narinesingh et al., 2017), and monocular enucleation (Moro & Steeves, 2018) with the former, but not the latter, suggesting increased integration in the SIFI. Studies investigating the effect of mild age-related hearing loss (Gieseler et al., 2020) and hearing aid use in the SIFI (Gieseler et al., 2018) have shown that participants with mild age-related hearing loss were less susceptible to the SIFI compared with older adults with a similar degree of hearing loss who habitually used hearing aids (Hearing Aid Users, HAUs). This finding is consistent with current models of multisensory perception, in which more reliable auditory input (relative to vision) would shift perception towards audition, which, in the SIFI, corresponds to a stronger illusion.

The HAUs in Gieseler et al. (2018) included older adults who had used hearing aids on average for 5.9 years ($SD = 4.5$). Because TILDA is a longitudinal study, with self-reports of eye disease status, cataract removal and hearing aid use recorded every 2 years, we were able to identify two broad categories of HAUs; longer-term (>4 years) and shorter-term (<2 years) HAUs. This enabled us to investigate whether differences in multisensory integration manifest within the first few years of hearing aid use. Similarly, we aimed to examine whether clinical intervention to improve vision (cataract removal) might shift perception towards visual information in the SIFI. The implications of this would be that the SIFI could be used to measure sensory reweighting following interventions aimed to improve sensory function. The data available within the TILDA study allowed us to explore both of these possibilities, in addition to the effect of eye disease.

Importantly, we recognise that the trajectory of adaptation and recovery to hearing aids and cataract removal are different: patients recover relatively quickly from cataract surgery. Rosen, Rubowitz, and Assia (2009) found that 67% of older adults over 90 years old showed improved visual acuity

6–8 months post-surgery. Conversely, adjustment to hearing aids appears more demanding (Dawes et al., 2014; Dawes & Munro, 2016). The time frames used to compare long and short-term effects of intervention in the current study (>4 years and <2 years) were selected due to the structure and time frame of data collection within TILDA, which occurs once every 2 years (see Donoghue et al., 2018 for a recent cohort update). For this reason, our investigation of the effect of cataract removal and hearing aid use remain exploratory in nature. Nevertheless, this investigation provides important insights into the long-term outcomes of common clinical interventions to restore sensory function in ageing.

On the basis of existing literature, we hypothesised¹:

- 1) Individuals with eye disease will be more susceptible to SIFI and show larger visual gains (i.e., use audition to improve visual judgements) compared with healthy, age-matched controls.

Second, we focused on the effect of cataract removal and hearing aid use. We hypothesised that participants with a more recent intervention would give less weighting to the previously impaired sense, compared with healthy controls and individuals who have had longer to adapt to sensory intervention. Based on this, our hypotheses were:

- 2) Individuals who received bilateral cataract removal most recently relative to assessment (i.e., < 2 years) will show integration in favour of audition (stronger SIFI susceptibility and visual gain) compared with healthy controls and those who received cataract removal >4 years prior to SIFI assessment.
- 3) Individuals acquiring hearing aid devices most recently relative to SIFI assessment (i.e., < 2 years) will show integration in favour of vision (weaker SIFI susceptibility and reduced visual gains) compared with controls and those who have used hearing aids for longer (i.e., > 4 years).

These hypotheses are based on the main premise of reliability weighting models of multisensory perception. Notably, with regards to hypothesis 3, if recovery of visual function following cataract surgery occurs quickly, as discussed, we might expect no difference in performance between healthy controls and patients with cataracts removed. Through investigating these effects, we aimed to investigate and identify any unexplored impact of eye disease and clinical interventions to restore sensory function upon multisensory integration in ageing. In turn, this may help in determining whether the SIFI task could be used as an approach to assess sensory reweighting during disease and following treatment.

¹ Project information, preregistration and materials can be viewed at <https://osf.io/7ubdn/>. Following feedback, three deviations from our planned analysis were made i) we no longer focus on hypothesis 2 in our preregistration, a time-stamped justification is noted on our OSF project page; ii) we incorporated retinal photographs for more objective grouping; iii) we used more flexible mixed-effects models in lieu of planned ANOVAs. Critically (iii) did not change our findings reported in models 1, 3 and 4 (model 2 pertains to retinal photographs).

2. Method

2.1. Participants

Participants were drawn from wave 3 of the Irish Longitudinal Study on Ageing (TILDA), a population representative sample of individuals aged 50+ from across the Republic of Ireland. Details of the sampling design have been provided in a previous study (Whelan & Savva, 2013). Participants completed a Computer Assisted Personal Interview (CAPI) carried out by a trained interviewer, in which they provided information regarding doctor diagnosed eye disease and clinical interventions (see Selection of intervention groups), as well as a comprehensive clinic-based health assessment, in which the SIFI was administered. Graded retinal photographs (used in analysis 2) were obtained within the healthcare assessment at wave 1 of TILDA. The study was approved by the Trinity College Faculty of Health Sciences Ethics Committee and conducted in accordance with the Declaration of Helsinki. Testing protocols conformed to GDPR. All participants provided written, informed consent when they first participated in the study and consent was repeated at wave 3 (the focus of this study). We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

2.1.1. Selection of eye disease groups

Sample size was determined by the number of individuals participating in the TILDA study (sampling procedure outlined in section 2.1) in addition to the inclusion/exclusion criteria outlined (Figs. 1 and 2). For analyses 1 and 2, we focused on the effect of eye disease on multisensory integration. For analysis 1, our grouping factor was self-diagnosed eye disease, resulting in four groups; Control, Cataracts, ARMD and Glaucoma (Fig. 1, upper). For analysis 2, our grouping factor was eye disease group diagnosed using retinal photographs (see procedure for details of protocol) obtained at wave 1 of TILDA (four years prior to SIFI assessment), this also produced four groups; Control, ARMD (soft drusen), ARMD (hard drusen) and Glaucoma (Fig. 1, lower). This second analysis was conducted to enable a more objective grouping of eye disease, due to possible limitations of self-reported diagnoses (Foreman et al., 2017). Because cataracts cannot be diagnosed using retinal photographs, we limited this analysis to glaucoma and two types of ARMD compared with controls.

Fig. 1 shows the questions asked regarding eye disease and criteria used to select participants for comparison of eye disease groups, identified based on self-report (analysis 1) and retinal photographs (analysis 2), in comparison to selected control groups. Due to very large inequalities in the sample size available for each group, participants were selected from the larger groups to match the number of participants available in the smallest group (Glaucoma; $n = 41$ in analysis 1 and $n = 43$ in analysis 2). Participants were selected to match the age of the smallest group as closely as possible however age was held as a covariate across analyses to control for between-group differences (in addition to several other

covariates, discussed later). Due to the large number of participants falling into the control group that also had retinal photographs at wave 1, we were able to further exclude participants from the control group that were diagnosed at wave 1 with possible eye diseases. Participants reporting use of a hearing aid were not included in analyses investigating eye disease. Descriptives for each group are shown in [Supplementary Tables 1 and 2](#)

2.1.2. Selection of intervention groups

The aim of analyses 3 and 4 was to explore the longer- and shorter-term effects of clinical interventions to improve sensory function (bilateral cataract removal and hearing aids) upon multisensory integration. For analysis 3 our grouping factor was time since cataract removal and for analysis 4 our grouping factor was time since hearing aid acquisition, where “time” refers to the TILDA wave at which treatment was reported (see Fig. 2 for questions asked and selection procedure). For both of these analyses grouping was determined by the timing of data collection within TILDA, which takes place every 2 years. We therefore isolated 4 groups, those receiving intervention >4 years prior to SIFI assessment (i.e., reporting at wave 1), 2–4 years prior (i.e., reporting at wave 2 but not wave 1), or <2 years prior (i.e., reporting at wave 3 but not wave 1 or 2) and controls. Due to the limited number of participants falling in the 2–4 year groups, we selected only participants in the >4 year and <2 year groups to compare with controls, thus enhancing the statistical power of our analyses. As with analyses 1 and 2, participants were selected from the larger groups to match the age of the smallest groups as closely as possible, but age was held as a covariate in analyses. Descriptives for each group are shown in [Supplementary Tables 3 and 4](#)

For analyses 3, the control group consisted of participants who did not report cataracts (or any other eye diseases), and therefore did not report bilateral cataract removal at any wave of TILDA. We also removed participants from the control group who were diagnosed at wave 1 with eye disease based on their retinal photograph. The treatment groups for analysis 3 consisted only of participants reporting cataract removal for both eyes and not reporting any other eye disease. For analysis 4, our control group consisted of participants who never reported the use of a hearing aid, never reported any eye diseases and were not diagnosed with eye diseases based on their retinal photograph. The treatment groups in analysis 4 also never reported any eye disease.

2.2. Procedure

2.2.1. The Sound-Induced Flash Illusion

The specific task based on the Sound-Induced Flash Illusion (SIFI) used in TILDA was described elsewhere (see [Hernández et al., 2019; Hirst, Setti, Kenny, & Newell, 2019](#)). Briefly, participants were seated in front of a computer (Dell Latitude E6400 with Intel Core 2 Duo CPU, 2 Gb RAM, using Windows 7 Professional OS) and instructed to look at the fixation cross at the centre of the screen. All stimuli were presented via Presentation software (<https://www.neurobs.com/>). If the participant usually wore glasses or hearing aids they also wore them during the SIFI assessment. A fixation cross marked the start of each trial and appeared for

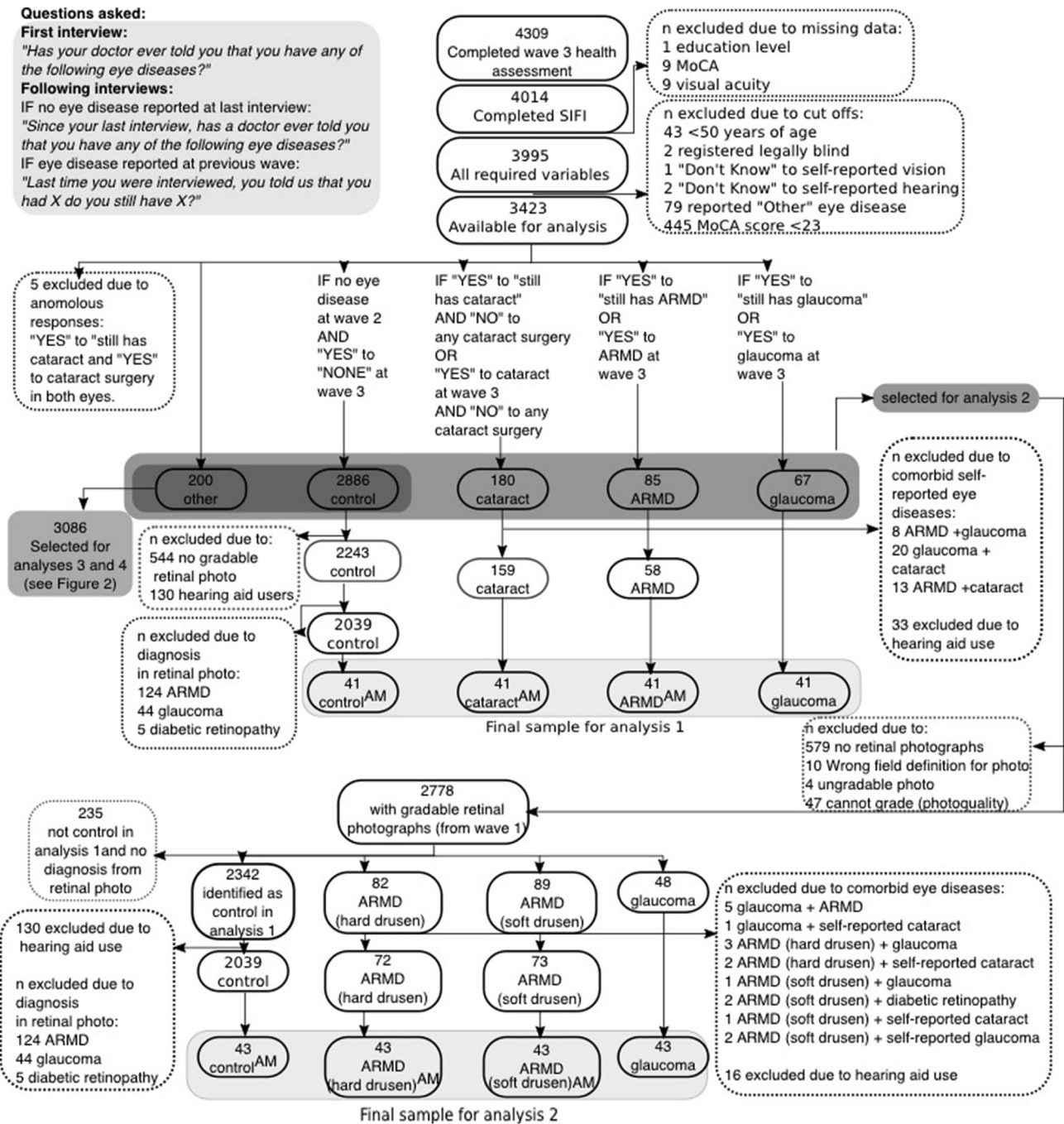


Fig. 1 – Selection criteria for participants available for comparison of eye disease based upon self-reported diagnosis (analysis 1, upper figure) and retinal photographs (analysis 2, lower figure) from wave 3 of TILDA. MoCA = Montreal Cognitive Assessment; ARMD = Age-Related Macular Degeneration; AM = Approximately matched (i.e., to ensure comparable sample sizes between groups, participants were selected from the larger groups to match the age of the smallest group as closely as possible. However age was held as a covariate across analyses).

1000 msec. The visual and/or auditory stimuli were then presented. The visual stimulus comprised a white disc (1.5° visual angle, 32 fl luminance), projected onto a black background 5 cm below the central fixation cross for 16 msec. Viewing distance was approximately 60 cm. Auditory beeps were brief bursts of 3500 Hz sounds (10 msec, 1 msec ramp), presented at approximately 80 dB via the inbuilt speakers in the laptop.

Table 1 shows all possible trial types. Each trial type was presented twice within a block and in random order. Before each testing block, a practice phase was presented comprising of one trial from each condition (with the exception of those indicated in Table 1). Participants were asked to count the number of visual flashes. Once a response was provided, the nurse, who sat near the participant, recorded the participant's vocal responses by pressing corresponding number keys on a

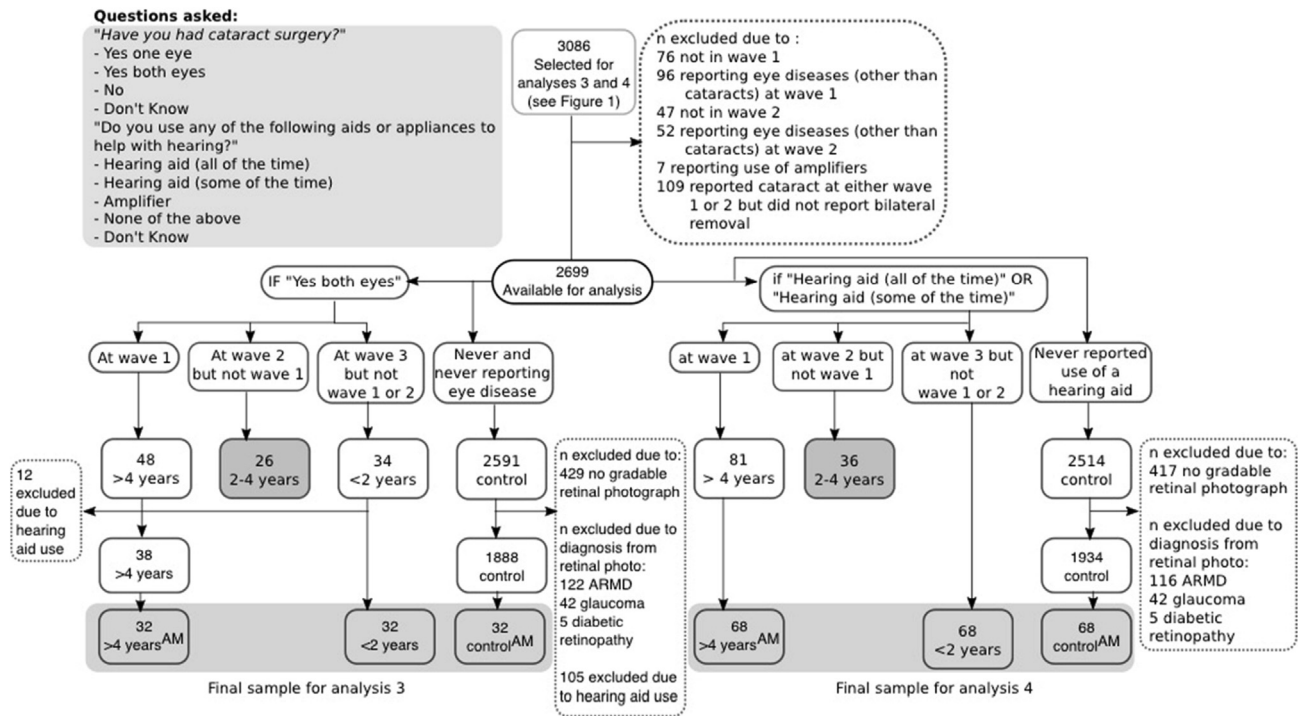


Fig. 2 – Selection criteria for participants available for analysis 3 and 4. ARMD = Age-Related Macular Degeneration; AM = Approximately matched (i.e., to ensure comparable sample sizes between groups, participants were selected from the larger groups to approximately match the n of the smallest group in terms of age, to within 7 years. However age was held as a covariate across analyses).

Table 1 – Parameters used for each condition. SOA = Stimulus-Onset Asynchrony, in which negative values indicate the second beep was presented before the flash–beep pair (i.e., “pre” condition) and positive values indicate the second beep lagged the flash–beep pair (“post” condition). Unimodal auditory conditions were presented in a separate block in which subjects reported the number of beeps, all other conditions required subjects to count the number of flashes.* = not included in the multisensory practice block.

Block	Condition label		Number of beeps	Number of flashes	SOAs (ms)
Multisensory	Illusory (SIFI)	2B1F	2	1	–230*, –150*, –70*, 70, 150, 230
		2B2F	2	2	70, 150*, 230*
	Non Illusory	1B1F	1	1	n/a
		0B2F	0	2	70
		0B1F	0	1	n/a*
Auditory	Unimodal auditory	2B0F	2	0	70, 150, 230
		1B0F	1	0	n/a

laptop. The space bar had to be pressed to continue to the next trial. Unimodal auditory trials were presented first in a separate block; in this block participants were asked to count the number of beeps.

2.2.2. Retinal photographs and image classification

The procedure for obtaining retinal photographs and grading eye disease was identical to that previously described in the TILDA cohort (Akuffo et al., 2015). Fundus photographs were obtained at wave 1 of TILDA with a NIDEK AFC-210 non-mydratic auto-fundus camera through a non-dilated pupil. Retinal photographs were graded at MPRG, Vision Research Centre, Waterford, Ireland, by a masked grader (KOA) who was trained and certified at the MEH Reading Centre. Grading was carried out under the

supervision of the MEH Reading centre manager (TP) using a modified version of the International Classification and Grading System for ARMD (Bird et al., 1995). Drusen represent lipid deposits under the retina recognised as hallmark indicators of ARMD (Abdelsalam et al., 1999; Kang & Grossniklaus, 2007). Drusen were categorised as “hard” or “soft” based on their size and edge morphology. Hard drusen were defined in TILDA as >10 deposits of size <63 µm, soft drusen were defined as one or more drusen of size ≥125 µm. Glaucoma was identified based on the presence of notching, disc haemorrhages or vertical cup to disc ratio greater than .6. Grading was conducted for both eyes and each participant was grouped based on the overall predominant age-related macular degeneration in both eyes (representing the dominant AMD phenotype for participant).

2.3. Data analysis

Statistical analyses were performed in the R statistical programming environment (R studio version 3.6.1; R [CoreTeam, 2018](#)). Analyses 1 and 2 examined the effect of eye disease (self reported and diagnosed via retinal photography respectively) on multisensory integration (SIFI susceptibility and visual gain). As previously described, analysis 2 was conducted to assess the association using an objective measure of eye disease, due to possible limitations of self-reported diagnoses ([Foreman et al., 2017](#)). Analyses 3 and 4 investigated the longer- and shorter-term effects of clinical interventions (bilateral cataract removal and hearing aids respectively) to improve sensory function upon multisensory integration.

2.3.1. Outcome measures

SIFI susceptibility represented accuracy for judging how many flashes were presented when one flash was presented with two beeps (2B1F). Lower accuracy, judging one flash as two, thus indicates higher SIFI susceptibility and stronger integration.

Visual gain represented accuracy for judging how many flashes were presented when 2 flashes were presented unimodally, with no beeps (0B2F), versus crossmodally, with two beeps (2B2F). We compared unimodal and crossmodal conditions both with 70 msec SOA, because flashes were never presented unimodally with SOAs of 150 or 230 msec. Visual gain was therefore reflected as better accuracy for judging two flashes presented with two beeps compared with judging 2 flashes presented alone. Equivalent auditory gain was not explored because participants were never asked to judge the number of beeps under multisensory conditions.

2.3.2. Statistical models

Both SIFI susceptibility and visual gain were proportion correct. As there were two trials per condition, these variables were considered discrete (i.e., participants scored 0, .5 or 1 proportion correct). Generalised logistic mixed-effect models were therefore used to predict accuracy for all analyses. These models were implemented using “glmer” in the “lme4” package (family = “binomial”) ([Bates et al., 2015](#)).

For all our analyses (1–4), dependent variables were SIFI susceptibility and visual gain. They were investigated in separate models. For analyses 1, the fixed effect was self-reported eye disease (4 groups: Cataracts, ARMD, Glaucoma and controls). For analyses 2, the fixed effect was eye disease diagnosed via retinal photography (4 groups: ARMD (soft drusen), ARMD (hard drusen), Glaucoma and controls). For analyses 3 and 4, fixed effects were bilateral cataract removal and hearing aids respectively (3 groups: >4 years, <2 years and controls). For all analyses, control groups were set as the reference level. When the dependent variable was SIFI susceptibility, the models also included as fixed factors “SOA” (3 levels: 70, 150 and 230 msec) and flash beep pairing (2 levels: Pre and Post, with “Pre” indicating the second beep preceded the flash–beep pair). An SOA × Group (self-reported eye disease; objectively diagnosed eye disease; cataract removal; hearing aid respectively) interaction term was also added to the models. When the dependent variable was visual gain, the

models also included the factor “sensory condition” to compare accuracy for judging two flashes presented unimodally (0B2F) or crossmodally (2B2F) at the single SOA of 70 msec (therefore 2 levels: 0B2F and 2B2F). A Sensory Condition × Group interaction term was also added to these models. For all models, the significance of the interaction term, grouping factor and SOA (where applicable) were assessed through likelihood ratio tests. For analyses 3 and 4, if the factor of group was significant, we further compared longer-term and shorter-term groups through resetting the reference level as the shorter-term group (rather than the controls). A Bonferroni corrected alpha of .025 was used to adjust for multiple comparisons.

All our models included the covariates age, sex, education (Primary, Secondary or Third/higher), MoCA score, accuracy for judging 1 flash in the 1B1F condition, self-reported vision and hearing (ranging from 1 = Excellent to 5 = Poor), visual acuity score [calculated as $100 - 50 * \text{LogMAR visual acuity score}$ so that higher scores indicate better acuity as in [Donoghue et al. \(2013\)](#)], accuracy for judging 2 beeps at 70 msec (2B0F) and accuracy for judging 2 flashes at 70 msec (0B2F). This final factor was not included as a predictor in the analyses with visual gain because this score formed the unimodal dimension of the dependant variable. For all our models, participant ID was the random intercept. All measures were centred and scaled prior to analysis to limit multicollinearity. In the results section, we report models fully adjusted for these covariates and focus on the association between our outcomes measures and fixed effects; the individual effects of covariates can be found in the [Supplementary Material](#).

3. Results

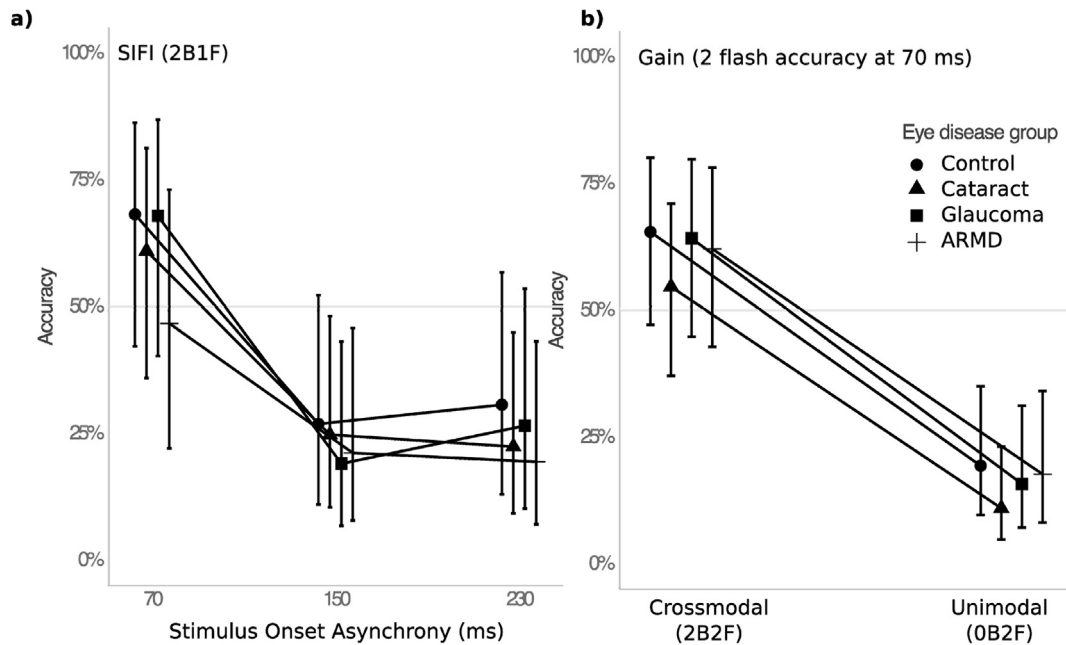
3.1. Eye disease groups

[Fig. 3](#) shows the predicted probability of making a correct response on illusory 2B1F trials (lower accuracy corresponds to stronger SIFI susceptibility) and on unimodal visual (0B2F) versus crossmodal (2B2F) trials (better accuracy for crossmodal vs unimodal conditions indicates visual gain) in self-reported eye disease groups (analysis 1) and eye disease groups identified by retinal photograph (analysis 2).

3.1.1. SIFI susceptibility

Accuracy in the 2B1F condition was significantly influenced by SOA in both analysis 1 and 2. Including the term “SOA” in the model significantly improved model fit (analysis 1; $\chi^2_{(2)} = 155.57$, $p < .001$, analysis 2; $\chi^2_{(2)} = 124.67$, $p < .001$). The odds of making a correct response was significantly lower at both 150 msec (analysis 1; OR = .17, CI = .09–.31, $p < .001$, analysis 2; OR = .24, CI = .14–.41, $p < .001$) and 230 msec SOA (analysis 1; OR = .21, CI = .11–.37, $p < .001$, analysis 2; OR = .29, CI = .17–.50, $p < .001$) relative to the 70 msec SOA reference condition. The odds of making a correct response was lower when the second beep preceded the flash–beep pair, i.e., in the ‘pre’ than ‘post’ condition (analysis 1; OR = .57,

Analysis 1 (self-reported eye disease)



Analysis 2 (Retinal photographs)

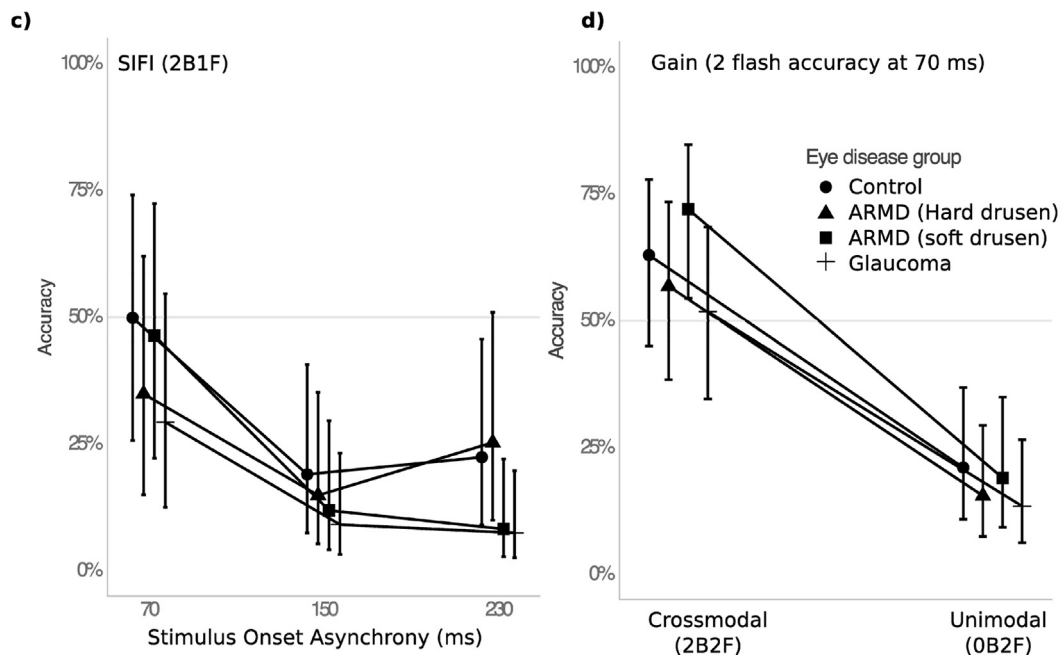


Fig. 3 – Predicted probability of making a correct response in participants self-reporting eye disease (analysis 1, panels a and b) and diagnosed with eye diseases from retinal photographs (analysis 2, panels c and d). ARMD = Age-Related Macular Degeneration. Results are shown for the illusory 2B1F condition (panels a and c) and for the crossmodal 2B2F condition and unimodal 0B2F condition (panels b and d respectively), in which stimuli were always presented with 70 msec SOA. Error bars reflect 95% confidence intervals of the models.

CI = .44–.73, $p < .001$, analysis 2; OR = .57, CI = .45–.73, $p < .001$).

In analysis 1, including the grouping factor of self-reported eye disease did not significantly improve model fit ($\chi^2_{(3)} = 1.595$, $p = .660$) and neither did the self-reported eye disease by SOA interaction term ($\chi^2_{(6)} = 5.518$, $p = .479$). In analysis 2, including the grouping factor of

diagnosed eye disease group did not significantly improve model fit ($\chi^2_{(3)} = 4.737$, $p = .192$), but the interaction term between diagnosed eye disease group and SOA significantly improved model fit ($\chi^2_{(6)} = 19.175$, $p = .004$). This interaction occurred because in the ARMD (soft drusen) group the odds of making a correct response at 230 msec was 36% lower than would be predicted based on performance at 70 msec

SOA compared with controls (OR = .36, CI = .15–.83, $p = .016$; Fig. 3c).

3.1.2. Visual gain

Participants were less likely to judge 2 flashes correctly under unimodal than crossmodal conditions (analysis 1; OR = .13, CI = .06–.28, $p < .001$, analysis 2; OR = .16, CI = .07–.33, $p < .001$). The low unimodal accuracy for perceiving two flashes at 70 msec SOA is in line with reduced visual temporal sensitivity in ageing (e.g., reduced flicker sensitivity Lachenmayr et al., 1994). A benefit of crossmodal stimulus presentation for judging the number of flashes, visual gain, was therefore evident. In analysis 1 and 2, including eye disease group did not significantly improve model fit (analysis 1; $\chi^2_{(3)} = .298$, $p = .960$, analysis 2; $\chi^2_{(3)} = 6.038$, $p = .110$) nor did the interaction between eye disease and stimulus condition ($\chi^2_{(6)} = 3.138$, $p = .371$, analysis 2; $\chi^2_{(3)} = 1.178$, $p = .758$).

3.2. Intervention groups

3.2.1. SIFI susceptibility

For both analysis 3 and 4 considering SOA significantly improved model fit (Fig. 4; analysis 3; $\chi^2_{(2)} = 70.968$, $p < .001$, analysis 4; $\chi^2_{(2)} = 217.78$, $p < .001$). The odds of making a correct response in the 2B1F condition was significantly lower at both 150 msec (analysis 3; OR = .30, CI = .16–.56, $p < .001$, analysis 4; OR = .31, CI = .2–.48, $p < .001$) and 230 msec (analysis 3; OR = .30, CI = .16–.56, $p < .001$, analysis; 4 OR = .34, CI = .22–.53, $p < .001$) relative to the 70 msec SOA reference. As in our first set of analyses, correct responses were less likely if the second beep preceded the flash beep pair (analysis 3 OR = .52, CI = .38–.72, $p < .001$, analysis 4 OR = .57, CI = .46–.71, $p < .001$).

In analysis 3, the effect of cataract removal group failed to reach significance ($\chi^2_{(2)} = 2.006$, $p = .367$) as did the interaction between group and SOA ($\chi^2_{(4)} = 4.159$, $p = .385$). In analysis 4, including the HAU group in the model improved model fit ($\chi^2_{(2)} = 7.882$, $p = .019$) as did the SOA by HAU group interaction ($\chi^2_{(6)} = 23.52$, $p < .001$). The main effect of HAU group occurred because the long-term HAUs were more accurate than the controls (OR = 5.72, CI = 2.48–13.22, $p < .001$) and the <2 year group (OR = 3.26, CI = 1.46–7.30, $p = .004$); the difference between the <2 year group and control group failed to reach significance (OR = .57, CI = .26–1.24, $p = .155$).

The interaction between HAU group and SOA occurred because long-term HAUs were less accurate at 150 msec than would be predicted by the model given their higher accuracy relative to the reference groups at 70 msec (control as ref: OR = .43, CI = .22–.85, $p = .015$, <2 year as ref: OR = .86, CI = .44–1.72, $p = .677$) and 230 msec SOA (controls as ref: OR = .21, CI = .11–.42, $p < .001$, <2 year as ref: OR = .37, CI = .18–.74, $p = .005$). Thus, long-term HAUs were less susceptible to the SIFI at shorter SOAs but appeared susceptible to the illusion at longer SOAs. Short-term HAUs did not significantly differ from controls overall (OR = .57, CI = .26–1.24, $p = .155$). Furthermore, considering our Bonferroni corrected alpha of .025 for this analysis, the predicted odds of making a correct response in the <2 year group did not significantly

differ from what would be expected, considering baseline differences with controls, at 150 msec (OR = 2.00, CI = 1.04–13.83, $p = .038$) and 230 msec (OR = 1.76, CI = .93–3.34, $p = .083$).

3.2.2. Visual gain

As with our first set of analyses, participants were less likely to judge 2 flashes correctly under unimodal versus crossmodal conditions (analysis 3; OR = .13, CI = .06–.32, $p < .001$, analysis 4; OR = .17, CI = .09–.30, $p < .001$). Including intervention group in the models failed to significantly improve the fit of the model for cataract removal in analysis 3 ($\chi^2_{(2)} = 4.926$, $p = .085$) and HAU in analysis 4 ($\chi^2_{(2)} = 4.085$, $p = .1297$) as did the interaction between intervention group and sensory condition (analysis 3; $\chi^2_{(2)} = 2.853$, $p = .240$, analysis 4; $\chi^2_{(2)} = 2.575$, $p = .276$).

4. Discussion

In this study, we explored whether multisensory integration is influenced by common age-related eye disease (self-reported and diagnosed via retinal photography), as well as clinical interventions to improve sensory function in ageing (bilateral cataract removal and hearing aid use). Multisensory integration was measured using both susceptibility to the Sound-Induced Flash Illusion (SIFI) and improved visual judgements under crossmodal versus unimodal conditions (visual gain).

In analysis 1, the self-reported eye disease group did not influence integration, in terms of SIFI susceptibility or visual gain. Similarly, in analysis 2, the performance of participants diagnosed with glaucoma or ARMD (hard drusen) using retinal photographs, did not significantly differ from controls. However, participants with ARMD (soft drusen) appeared more susceptible to the SIFI at long SOAs, given that performance at short SOAs was similar to controls. In analysis 3, self-reported bilateral cataract removal did not influence SIFI susceptibility nor visual gain in comparison with controls. However, in analysis 4, there was an effect of hearing aid use and an interaction between HAU group and SOA. Long-term HAUs were less susceptible to SIFI at short SOAs compared with controls although they did show SIFI susceptibility at longer SOAs. We interpret these findings as indicating subtle differences in multisensory perception in those diagnosed with ARMD (soft drusen) as well as showing an impact of longer-term hearing aid use on multisensory integration. In our interpretation of these results, we consider stronger illusion perception at longer SOAs to reflect continued integration, based on previous evidence that the time window in which the SIFI is perceived reflects the width of the TBW (for a review see Hirst et al., 2020).

4.1. Eye disease and multisensory integration

To our knowledge, the current study was the first to investigate the effect of age-related eye disease on multisensory perception by measuring SIFI susceptibility and visual gain in an older adult population. Previous studies have investigated the effect in young adults with amblyopia (Narinesingh et al.,

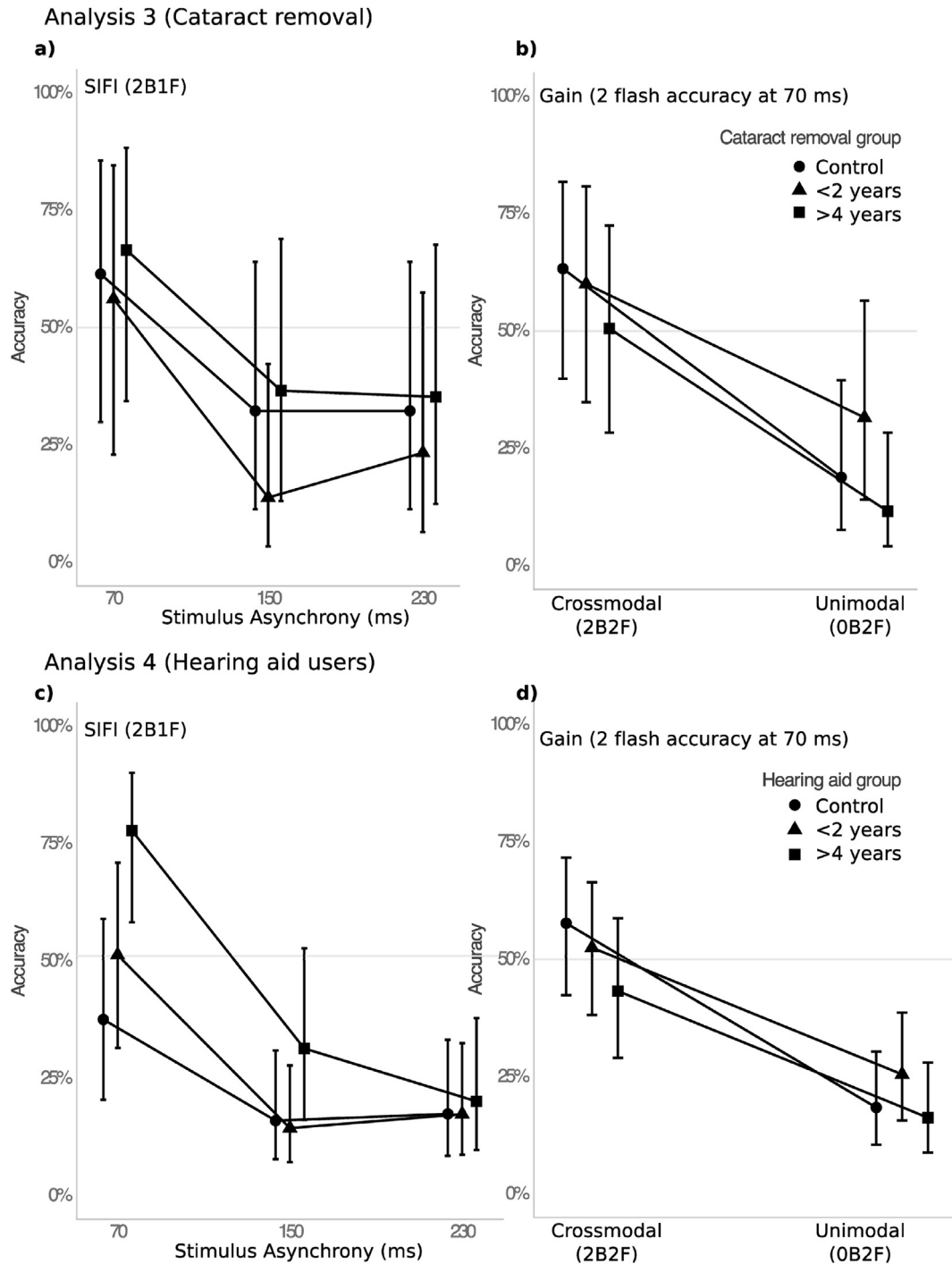


Fig. 4 – Predicted probability of making a correct response in participants self-reporting bilateral cataract removal (analysis 3, panels a and b) and hearing aid use (analysis 4, panels c and d). Results are shown for the illusory 2B1F condition (panels a and c) and for the crossmodal 2B2F condition and unimodal 0B2F condition (panels b and d respectively), in which stimuli were always presented with 70 msec SOA. Error bars reflect 95% confidence intervals of the models.

2017) and monocular enucleation (Moro & Steeves, 2018). The former of these found sustained SIFI susceptibility at longer SOAs, whilst the latter observed no evidence of SIFI susceptibility in participants with one eye. The literature examining the effects of eye disease on the SIFI phenomenon is therefore sparse and equivocal. In the present study, we hypothesised that older adults with eye disease would show stronger SIFI

susceptibility and stronger use of auditory information to aid visual judgements (visual gain). These hypotheses were made on the knowledge that sensory function in ageing has been shown to systematically alter susceptibility to SIFI in line with reliability weighting (Hirst et al., 2019) and the idea that increased integration in ageing might serve a compensatory function (de Dieuleveult et al., 2017).

In contrast to our hypotheses, we found that self-reported eye disease did not significantly influence multisensory integration. Because self-reported eye disease might be considered unreliable (Foreman et al., 2017) we followed this with an analysis using retinal photographs derived at wave 1 of TILDA, 4 years prior to the administration of the SIFI assessment. The findings from these analyses supported our previous result that participants with glaucoma did not differ from controls in SIFI susceptibility or visual gain. In terms of ARMD, we found that participants graded as having soft drusen lesions, but not hard drusen lesions, were more susceptible to SIFI at longer SOAs than predicted, given their baseline performance. Whilst hard drusen may occur at a younger age and generally have good prognosis, soft drusen are identified as larger lesions that precede ARMD and the associated risk of visual loss (Abdelsalam et al., 1999).

There are several reasons why soft ARMD might link with increased illusion perception. First, ARMD has been associated with slower visual processing speed, for example, those with ARMD show delayed latency of event-related potentials associated with face perception (Vottonen et al., 2017) and also manifest increased temporal threshold for letter detection (Cheong et al., 2007), which has been linked to slower reading speed. Slower visual processing in ARMD could further reduce the temporal reliability of visual information and result in increased illusion perception at longer SOAs in the SIFI. To our knowledge, visual processing speed has not been explicitly associated with the SIFI, therefore this represents an interesting avenue for future research. Second, it has been hypothesised that macular degeneration may result in reduced connectivity between the visual cortex and association brain regions which are known to have multisensory functions, such as the intra-parietal sulcus (Beauchamp et al., 2010), resulting in reduced visual weighting. Our findings provide partial support for this prediction, as soft drusen lesions were associated with stronger influence of audition at long SOAs in the SIFI. Prolonged susceptibility to the SIFI at long SOAs is a characteristic feature of ageing (e.g., McGovern et al., 2014), that has been associated with fall risk (Setti et al., 2011; Stapleton et al., 2014), mild cognitive impairment (Chan et al., 2015) and lower scores of general cognitive function (Hernández et al., 2019). Importantly, the different pattern of multisensory integration in soft drusen reached significance even controlling for demographic, cognitive and sensory factors. This finding may therefore provide preliminary evidence of the SIFI as a behavioural probe of early changes in perceptual function in specific ocular pathology. However, contrary to what would be expected based on compensatory accounts of enhanced integration in ageing (de Boer-Schellekens & Vroomen, 2014; de Dieuleveult et al., 2017), we did not observe any statistically significant differences in visual gain in any eye disease group compared with controls.

Interestingly, we found no effect of glaucoma, a disease affecting peripheral vision, in analysis 1 or 2. A possible explanation of this is that visual field loss in glaucoma has been reported to be largely heterogeneous (Rudolf et al., 2008; Yousefi et al., 2018) and superior visual field loss is common. As such, it is possible that the region of visual space in which the visual stimulus was presented (the lower visual field) remained intact, despite possible glaucoma. A remaining

question for empirical work is therefore to address whether glaucoma influences multisensory integration when visual information is presented in a targeted region of the visual field known to be affected by the disease. Furthermore, in the current study, information regarding the duration of visual loss in clinical groups was not available. Future research should therefore examine whether the stage of disease progression, the duration of visual impairment and the specific region of the visual field affected by disease influences the effect of eye disease on multisensory perception.

4.2. Cataract removal and multisensory integration

Several studies have investigated the effects of bilateral cataract removal on multisensory integration (Chen et al., 2017; de Heering et al., 2016; Guerreiro et al., 2016; Putzar et al., 2007), although most investigated congenital cataracts, removed early in development. Here we investigated how cataract removal may influence multisensory integration in later life, an important topic given the prevalence of cataract removal in older adults. We did not find an effect of bilateral cataract removal group on SIFI susceptibility or visual gain.

The time frames selected to study cataract removal in this study were constrained by the timing of data collection within TILDA, which occurs every 2 years. However, several lines of evidence suggest that recovery from cataract removal occurs within the first year post-operation (Rosen et al., 2009). This recovery can also be observed in the neuroplastic changes that occur following surgery. Six weeks following unilateral cataract surgery, older adults show increases in occipital V2 grey matter, consistent with increased binocular integration following surgery (Lou et al., 2013). At 6 months, the structure and function of visual and cognitive brain regions shown to be affected by cataracts appear comparable to healthy controls (Lin et al., 2018). It has been shown that adults aged 46–69 years with retinitis pigmentosa (duration of blindness ranged 16–26 years) show age-normal levels of multisensory integration 1.5 years following retinal prosthesis implantation (Stiles et al., 2019). Collectively, and positively, this evidence suggests that recovery of visual function may happen within a shorter timeframe than we were able to probe in this study.

One interpretation of our findings is therefore that older adults reporting cataract removal manifest age-normal levels of multisensory function within the first few years post-surgery (in line with evidence of quick recovery from cataract surgery and the finding that multisensory function is resorted to normal following retinal prosthesis i.e., Stiles et al., 2019). However, as we did not find any effect of self-reported cataracts on multisensory integration in analysis 1, we cannot rule out that age-related cataracts do not influence multisensory perception as measured using the SIFI. An important question for further research is therefore to map multisensory integration prior to and in the immediate period following cataract surgery.

4.3. Hearing aid use and multisensory integration

Long-term Hearing Aid Users (HAUs) showed higher accuracy for judging 1 flash presented with two beeps, at 70 msec,

compared with the controls and short-term HAU. Although long-term HAUs were less susceptible to the SIFI at short SOAs compared with controls and short-term HAUs, they still appeared susceptible to long SOAs.

One explanation for reduced illusion susceptibility at short SOAs in long-term HAUs might be that these individuals are less able to perceive two auditory beeps, and are therefore less likely to respond “two flashes” (i.e., more likely to provide the correct “one flash” response) under illusory conditions. Hearing impairment is associated with reduced auditory gap detection (Feng et al., 2010; Madden & Feth, 1992) and HAUs in this study showed lower accuracy for judging two beeps under unimodal conditions at short SOAs (Supplementary Table 4). Nevertheless, accuracy for unimodal judgements of two beeps and two flashes at 70 msec were held as covariates within our model and the difference between HAUs and controls remained significant. Thus, altered temporal resolution alone might not be enough to account for between-group differences. Furthermore, hearing aid use has been shown to improve gap detection at 3 and 5 months following acquisition in older adults aged 60+ (Fonseca & Costa-Ferreira, 2015; Lessa & Costa, 2016). It is possible that the current findings indicate that HAUs are less likely to give weighting to audition during multisensory integration and therefore be less susceptible to the SIFI.

Gieseler et al. (2018) showed that mild hearing loss initially results in reduced SIFI susceptibility, but that susceptibility may be restored to age appropriate levels through hearing aid use (see also Gieseler et al., 2020 for a recent study on the effects of mild hearing loss on SIFI perception). Several important differences exist between our study and that of Gieseler et al. (2018), which might account for different results. First, our control and HAU groups were not matched with respect to hearing loss. HAUs did, however, self-report their hearing as worse relative to controls (Supplementary Table 4) and it has been suggested that self-report appears a valid indicator of hearing abilities (Kenny Gibson et al., 2014). Nevertheless, we did not have an objective audiometric assessment of each participant's hearing ability, therefore we cannot ascertain the extent to which the groups differed in hearing function nor can we rule out the possibility of undetected hearing impairments in our control group. Second, we were not able to determine the precise nature of hearing aid use in terms of duration of use, pattern of use and type of hearing aid used. Gieseler et al. (2018) described habitual hearing aid use with an average duration of use for 5.9 years ($SD = 4.5$). It is possible that the HAUs in our ‘>4 year’ group had been using hearing aids for longer than the HAUs in the Gieseler et al. (2018) study. Furthermore, our HAU groups may have contained unilateral or bilateral HAUs. Remaining questions in the field of hearing aid use are therefore whether duration of use, pattern of use, type of hearing aid used and asymmetry in hearing function influence multisensory perception.

Nevertheless, our findings suggest differences in multisensory perception in long-term HAUs possibly indicative of reduced temporal resolution. Multisensory integration likely plays an important function in HAUs including speech comprehension (Stevenson et al., 2017) and memory for speech information (Frtusova & Phillips, 2016). Identifying whether long-term hearing aid use impacts the ability to integrate multisensory inputs and whether this has negative

consequences is therefore an important avenue for future research.

4.4. Further considerations

Several further observations were made in the current study that should be considered. Firstly, in this study and previous analyses of the TILDA data (Hernández et al., 2019), we found that susceptibility was lowest at 70 msec. This is a different pattern of effects to that seen in young adults (Shams et al., 2000) but is a characteristic pattern that has been reported across multiple studies of ageing (Hirst et al., 2020). It is likely that this results from a reduced ability to discriminate two beeps presented within a short SOA with older age. Second, we observed that susceptibility to the illusion was higher in the ‘pre’ than ‘post’ condition, when the second beep preceded the flash–beep pair. Hernández et al. (2019) reported a similar pattern of effects in the larger TILDA cohort (see Figure 2 of Hernández et al., 2019) however the effect was not statistically tested. Interestingly, this effect differs from previously reported effects in which the “right side” of the TBW plot, that is when the beep follows the flash, appears wider (Conrey & Pisoni, 2006; Dixon & Spitz, 1980; Stevenson et al., 2012, 2010; Van Atteveldt et al., 2007; van Wassenhove et al., 2007; Vroomen & Keetels, 2010). It is likely that the asymmetrical pattern of the TBW changes with age. In childhood, the TBW appears more symmetrical compared with young adults (Hillock et al., 2011). However, despite a likely change in the symmetry of the TBW across the lifespan, few studies have investigated this in ageing. A recent review of the SIFI showed that 9 studies have manipulated SOA in the SIFI with older adult groups, with only 3 of these (including the TILDA study) including an SOA condition in which the beep preceded the flash–beep pair (Hirst et al., 2020). It might, therefore, be of interest to understand whether symmetry in the TBW assessed using the SIFI changes in ageing.

In order to collect data on multisensory function within a large-scale cohort study such as TILDA, the duration of testing is necessarily limited. The SIFI task within TILDA thus contained fewer conditions than other SIFI studies. Only three SOAs were tested across trials, each with a “Pre” and “Post” version, each trial was repeated only twice and we did not have any illusory “fusion” conditions (e.g., presenting 2 flashes with 1 beep). With regards to “fusion” trials, fusion effects are consistently less reliable compared with fission (see Hirst et al., 2020 for a review). Shams et al. (2002) originally reported no fusion effects and interpreted this to support the conclusion that the illusion does not result from a response bias where participants respond to the auditory modality. Importantly, even when fusion is observed, this illusion does not increase with age as fission does (McGovern et al., 2014), thus the TILDA study includes fission trials only. However, this does limit our analysis, as we cannot use fusion to test response bias as in Shams et al. (2002). Nevertheless, given previous evidence that older adults also show SIFI changes consistent with changes in perception and not response bias (McGovern et al., 2014), and because the task explicitly instructs participants to report how many visual flashes they see, we do not believe the current results reflect participants responding to audition only.

With regards to SOA, it has been shown that the number of SOAs tested can directly influence performance on the SIFI (Chan et al., 2018), such that the inclusion of more SOAs enables the updating of perceptual priors, thus weakening SIFI susceptibility. Although Chan et al. (2018) found this occurred in both young and older adults, this effect was smaller in older adults, suggesting reduced ability to update perceptual priors based upon new information with ageing. It is possible that using more SOAs, and more trials, may have revealed differences between groups in terms of the ability to update perceptual priors based on new information. This is a question that can only be addressed by rigorous empirical assessment. Nevertheless, the SIFI effects observed in the TILDA study illustrate that multisensory integration can be determined via a brief assessment. This finding provides a promising outlook for assessing multisensory function in cases where prolonged testing is not possible or practical. Whilst the current study provides cross-sectional insight on the effect of eye disease, cataract removal and hearing aids on multisensory perception, an important future direction for the current work will be the longitudinal assessment of SIFI susceptibility as planned in the next wave of the TILDA study.

5. Conclusions

The aim of the current study was to examine whether age-related eye diseases (cataract, glaucoma, ARMD) and hearing impairment and clinical interventions to restore sensory function (cataract removal and hearing aids) alter multisensory perception in ageing. In contrast to our hypotheses, SIFI susceptibility in participant's self-reporting cataracts and participants with glaucoma (self-reported and determined by retinal photograph) did not significantly differ from that of their age-matched, healthy controls. However, subtle differences were observed in ARMD, such that participants diagnosed with soft drusen, but not hard drusen, were more susceptible to the SIFI at long SOAs. This suggests the SIFI might provide an early indicator of changes in perceptual function in specific types of ARMD. Future research is needed to examine whether stages of eye disease, disease duration, and region of visual damage influence multisensory integration. We also found no differences between individuals who had received bilateral cataract surgery, at any duration, and healthy controls, suggesting that, if cataracts do influence multisensory perception in ageing, this does not have long-term effects following removal. Finally, we observed that long-term hearing aid use resulted in less illusion susceptibility compared with controls. Importantly, as optimal multisensory integration is likely beneficial to HAUs, for example during speech comprehension, future research must tease apart the mechanisms underlying the impact of hearing aid use on multisensory function.

Author contribution statement

The Irish Longitudinal Study on Ageing (TILDA) is an interdisciplinary project co-ordinated by R.A.K. A.S and F.N.N

design the protocol for the Sound-Induced Flash Illusion incorporated into TILDA. R.J.H., A.S and F.N.N developed the analysis plan; R.J.H. conducted the analysis, with consultation from C.D.L, and prepared the manuscript for publication for which all authors provided feedback and revisions. Grading of retinal photographs was conducted by K.O.A. and T.P. All authors approved the final version of the manuscript for submission.

Open practices

The study in this article earned an Open Data – Protect Access badges for transparent practices. TILDA has a public database which includes unisensory and cognitive measures included in the current analysis available at <https://tilda.tcd.ie/data/accessing-data/> a list of studies using data from this database can be found at <https://tilda.tcd.ie/publications/papers/>. The SIFI data is planned to be included in future releases of the TILDA dataset, subject to General Data Protection Regulation and data management protocol in the TILDA team. In the meantime, data is accessible via a hotdesk system. For information on hotdesk applications see <https://tilda.tcd.ie/data/accessing-data/hotdesk/>. The analysis preregistration and experiment presentation scripts are also available here <https://osf.io/7ubdn/>.

Declaration of competing interest

None declared.

Acknowledgements

This work was supported by the Health Research Board (HRB), Ireland; Grant reference ILP-PHR-2017-014. The authors would like to thank Dr. John Newell (School of Mathematics, Statistics and Applied Mathematics, National University of Ireland Galway, Ireland) for his feedback on the statistical analysis performed within previous versions of this manuscript.

Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cortex.2020.08.030>.

REFERENCES

- Abdelsalam, A., Del Priore, L., & Zarbin, M. A. (1999). Drusen in age-related macular degeneration: Pathogenesis, natural course, and laser photocoagulation-induced regression. *Survey of Ophthalmology*, 44(1), 1–29. [https://doi.org/10.1016/S0039-6257\(99\)00072-7](https://doi.org/10.1016/S0039-6257(99)00072-7)
- Akuffo, K. O., Nolan, J., Stack, J., Moran, R., Feeney, J., Kenny, R. A., Peto, T., Dooley, C., O'Halloran, A. M., Cronin, H., & Beatty, S. (2015). Prevalence of age-related macular degeneration in the

- Republic of Ireland. *British Journal of Ophthalmology*, 99(8), 1037–1044. <https://doi.org/10.1136/bjophthalmol-2014-305768>
- Bates, D., Maechler, M., Bolker, B., & Steve, W. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Beauchamp, M. S., Pasalar, S., & Ro, T. (2010). Neural substrates of reliability-weighted visual-tactile multisensory integration. *Frontiers in Systems Neuroscience*, 4(25), 1–11. <https://doi.org/10.3389/fnsys.2010.00025>
- Bird, A. C., Bressler, N. M., Bressler, S. B., Chisholm, I. H., Coscas, G., Davis, M. D., de Jong, P. T. V. M., Klaver, C. C. W., Klein, B. E. K., Klein, R., Mitchell, P., Sarks, J. P., Sarks, S. H., Soubrane, G., Taylor, H. R., & Vingerling, J. R. (1995). An international classification and grading system for age-related maculopathy and age-related macular degeneration. *Survey of Ophthalmology*, 39(5), 367–374. [https://doi.org/10.1016/S0039-6257\(05\)80092-X](https://doi.org/10.1016/S0039-6257(05)80092-X)
- Chan, J. S., Connolly, S. K., & Setti, A. (2018). The number of stimulus-onset asynchronies affects the perception of the sound-induced flash illusion in young and older adults. *Multisensory Research*, 31, 175–190. <https://doi.org/10.1163/22134808-00002605>
- Chan, J. S., Kaiser, J., Brandl, M., Matura, S., Prvulovic, D., Hogan, M., & Naumer, M. (2015). Expanded temporal binding windows in people with mild cognitive impairment. *Current Alzheimer Research*, 12(1), 61–68. <https://doi.org/10.2174/1567205012666141218124744>
- Chen, Y. C., Lewis, T. L., Shore, D. I., & Maurer, D. (2017). Early binocular input is critical for development of audiovisual but not visuotactile simultaneity perception. *Current Biology*, 27(4), 583–589. <https://doi.org/10.1016/j.cub.2017.01.009>
- Chen, Y. C., & Spence, C. (2011). The crossmodal facilitation of visual object representations by sound: Evidence from the backward masking paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, 37(6), 1784–1802. <https://doi.org/10.1037/a0025638>
- Cheong, A. M. Y., Legge, G. E., Lawrence, M. G., Cheung, S.-H., & Ruff, M. A. (2007). Relationship between slow visual processing and reading speed in people with macular degeneration. *Vision Research*, 47(23), 2943–2955. <https://doi.org/10.1016/j.visres.2007.07.010>
- Conrey, B., & Pisoni, D. B. (2006). Auditory-visual speech perception and synchrony detection for speech and nonspeech signals. *The Journal of the Acoustical Society of America*, 119(6), 4065–4073. <https://doi.org/10.1121/1.2195091>
- CoreTeam, R. (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing. <http://www.r-project.org/>
- Dawes, P., Maslin, M., & Munro, K. (2014). “Getting used to” hearing aids from the perspective of adult hearing aid users. *International Journal of Audiology*, 53(12), 861–870. <https://doi.org/10.3109/14992027.2014.938782>
- Dawes, P., & Munro, K. J. (2016). Auditory distraction and acclimatization to hearing aids. *Ear and Hearing*, 38(2). <https://doi.org/10.1097/AUD.0000000000000366>
- de Boer-Schellekens, L., & Vroomen, J. (2014). Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly. *Experimental Brain Research*, 232(1), 253–262. <https://doi.org/10.1007/s00221-013-3736-5>
- de Dieuleveult, A. L., Siemonsma, P. C., van Erp, J. B. F., & Brouwer, A.-M. (2017). Effects of aging in multisensory integration: A systematic review. *Frontiers in Aging Neuroscience*, 9(80), 1–14. <https://doi.org/10.3389/fnagi.2017.00080>
- de Heering, A., Dormal, G., Pelland, M., Lewis, T., Maurer, D., & Collignon, O. (2016). A brief period of postnatal visual deprivation alters the balance between auditory and visual attention. *Current Biology*, 26(22), 3101–3105. <https://doi.org/10.1016/j.cub.2016.10.014>
- Dixon, N. F., & Spitz, L. (1980). The detection of auditory visual desynchrony. *Perception*, 9(6), 719–721. <https://doi.org/10.1068/p090719>
- Donoghue, O. A., McGarrigle, C. A., Foley, M., Fagan, A., Meaney, J., & Kenny, R. A. (2018). Cohort profile update: The Irish longitudinal study on ageing (TILDA). *International Journal of Epidemiology*, 1–13. <https://doi.org/10.1093/ije/dyy163>
- Donoghue, O. A., Ryan, H., Duggan, E., Finucane, C., Savva, G. M., Cronin, H., Loughman, J., & Kenny, R. A. (2013). Relationship between fear of falling and mobility varies with visual function among older adults. *Geriatrics and Gerontology International*, 14(4), 827–836. <https://doi.org/10.1111/ggi.12174>
- Feng, Y., Yin, S., Kieffe, M., & Wang, J. (2010). Temporal resolution in regions of normal hearing and speech perception in noise for adults with sloping high-frequency hearing loss. *Ear and Hearing*, 31(1), 115–125. <https://doi.org/10.1097/AUD.0b013e3181bb69be>
- Fonseca, G. C. R. da, & Costa-Ferreira, M. I. D. da (2015). The performance of the elderly with neurosensorial hearing loss in auditory processing tests: A longitudinal study. *Revista CEFAC*, 17(3), 809–818. <https://doi.org/10.1590/1982-0216201513114>
- Foreman, J., Xie, J., Keel, S., Van Wijngaarden, P., Taylor, H. R., & Dirani, M. (2017). The validity of self-report of eye diseases in participants with vision loss in the National Eye Health Survey. *Scientific Reports*, 7(1), 3–10. <https://doi.org/10.1038/s41598-017-09421-9>
- Freiherr, J., Lundström, J. N., Habel, U., & Reetz, K. (2013). Multisensory integration mechanisms during aging. *Frontiers in Human Neuroscience*, 7. <https://doi.org/10.3389/fnhum.2013.00863>
- Frtusova, J. B., & Phillips, N. A. (2016). The auditory-visual speech benefit on working memory in older adults with hearing impairment. *Frontiers in Psychology*, 7(APR), 1–14. <https://doi.org/10.3389/fpsyg.2016.00490>
- Garcia, S. E., Jones, P. R., Reeve, E. I., Michaelides, M., Rubin, G. S., & Nardini, M. (2017). Multisensory cue combination after sensory loss: Audio-visual localization in patients with progressive retinal disease. *Journal of Experimental Psychology: Human Perception and Performance*, 43(4), 729–740. <https://doi.org/10.1037/xhp0000344>
- Gieseler, A., Rosemann, S., Tahden, M., Wagener, K. C., Thiel, C., & Colonius, H. (2020). Linking audiovisual integration to audiovisual speech recognition in noise. *OSF Prepr.* September. <https://doi.org/10.31219/osf.io/46caf>
- Gieseler, A., Tahden, M. A. S., Thiel, C. M., & Colonius, H. (2018). Does hearing aid use affect audiovisual integration in mild hearing impairment? *Experimental Brain Research*, 236(4), 1161–1179. <https://doi.org/10.1007/s00221-018-5206-6>
- Gondan, M., Niederhaus, B., Rösler, F., & Röder, B. (2005). Multisensory processing in the redundant-target effect: A behavioral and event-related potential study. *Perception & Psychophysics*, 67(4), 713–726. <https://doi.org/10.3758/BF03193527>
- Guerreiro, M. J. S., Putzar, L., & Röder, B. (2016). Persisting cross-modal changes in sight-recovery individuals modulate visual perception. *Current Biology*, 26(22), 3096–3100. <https://doi.org/10.1016/j.cub.2016.08.069>
- Harrison, N. R., Wuerger, S. M., & Meyer, G. F. (2010). Reaction time facilitation for horizontally moving auditory-visual stimuli. *Journal of Vision*, 10(14), 1–21. <https://doi.org/10.1167/10.14.16>
- Hernández, B., Setti, A., Kenny, R. A., & Newell, F. N. (2019). Individual differences in ageing, cognitive status, and sex on susceptibility to the sound-induced flash illusion: A large-scale study. *Psychology and Aging*, 34(7), 978–990. <https://doi.org/10.1037/pag0000396>

- Hillock, A. R., Powers, A. R., & Wallace, M. T. (2011). Binding of sights and sounds: Age-related changes in multisensory temporal processing. *Neuropsychologia*, 49(3), 461–467. <https://doi.org/10.1016/j.neuropsychologia.2010.11.041>
- Hirst, R. J., McGovern, D. P., Setti, A., Shams, L., & Newell, F. N. (2020). What you see is what you hear: Twenty years of research using the Sound-Induced Flash Illusion. *Neuroscience and Biobehavioural Reviews*, 118, 759–774. <https://doi.org/10.1016/j.neubiorev.2020.09.006>
- Hirst, R. J., Setti, A., Kenny, R., & Newell, F. N. (2019). Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception. *Scientific Reports*, 9(19347). <https://doi.org/10.1038/s41598-019-55901-5>
- Holmes, N. P. (2009). The principle of inverse effectiveness in multisensory integration: Some statistical considerations. *Brain Topography*, 21(3–4), 168–176. <https://doi.org/10.1007/s10548-009-0097-2>
- Kang, S. J., & Grossniklaus, H. E. (2007). Histopathology of age-related macular degeneration. *Age-Related Macular Degeneration*, 223(May), 1–10. <https://doi.org/10.3109/9781420019865-2>. Second Edition.
- Keil, J. (2020). Double flash illusions: Current findings and future directions. *Frontiers in Neuroscience: Perception Science*. <https://doi.org/10.3389/fnins.2020.00298>
- Kenny Gibson, W., Cronin, H., Kenny, R., & Setti, A. (2014). Validation of the self-reported hearing questions in the Irish longitudinal study on ageing against the whispered voice test. *BMC Research Notes*, 7(1), 361. <https://doi.org/10.1186/1756-0500-7-361>
- Lachenmayr, B. J., Kojetinsky, S., Ostermaier, N., Angstwurm, K., Vivell, P. M. O., & Schaumberger, M. (1994). The different effects of aging on normal sensitivity in flicker and light-sense perimetry. *Investigative Ophthalmology and Visual Science*, 35(6), 2741–2748.
- Laurienti, P. J., Burdette, J. H., Maldjian, J. A., & Wallace, M. T. (2006). Enhanced multisensory integration in older adults. *Neurobiology of Aging*, 27(8), 1155–1163. <https://doi.org/10.1016/j.neurobiolaging.2005.05.024>
- Lessa, A. H., & Costa, M. J. (2016). The influence of cognition on the auditory skills of the elderly: Pre- and post-hearing aid fittings. *Audiology Communication Research*, 21, 1–7. <https://doi.org/10.1590/10.1590/2317-6431-2016-1686>
- Lin, H., Zhang, L., Lin, D., Chen, W., Zhu, Y., Chen, C., Chan, K. C., Liu, Y., & Chen, W. (2018). Visual restoration after cataract surgery promotes functional and structural brain recovery. *EBioMedicine*, 30, 52–61. <https://doi.org/10.1016/j.ebiom.2018.03.002>
- Lou, A. R., Madsen, K. H., Julian, H. O., Toft, P. B., Kjaer, T. W., Paulson, O. B., Prause, J. U., & Siebner, H. R. (2013). Postoperative increase in grey matter volume in visual cortex after unilateral cataract surgery. *Acta Ophthalmologica*, 91(1), 58–65. <https://doi.org/10.1111/j.1755-3768.2011.02304.x>
- Lovelace, C. T., Stein, B. E., & Wallace, M. T. (2003). An irrelevant light enhances auditory detection in humans: A psychophysical analysis of multisensory integration in stimulus detection. *Cognitive Brain Research*, 17(2), 447–453. [https://doi.org/10.1016/S0926-6410\(03\)00160-5](https://doi.org/10.1016/S0926-6410(03)00160-5)
- Madden, J. P., & Feth, L. L. (1992). Temporal resolution in normal-hearing and hearing-impaired listeners using frequency-modulated stimuli. *Journal of Speech and Hearing Research*, 35, 436–442. <https://doi.org/10.1044/jshr.3502.436>
- McGovern, D. P., Roudaia, E., Stapleton, J., McGinnity, T. M., & Newell, F. N. (2014). The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration. *Frontiers in Aging Neuroscience*, 6(250), 1–9. <https://doi.org/10.3389/fnagi.2014.00250>
- Meredith, M. A., Nemitz, J. W., & Stein, B. E. (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *The Journal of Neuroscience*, 7(10), 3215–3229. <https://doi.org/10.1523/JNEUROSCI.07-10-03215.1987>
- Meredith, M. A., & Stein, B. (1983). Interactions among converging sensory inputs in the superior colliculus. *Science*, 221(4608), 389–391. <https://doi.org/10.1126/science.6867718>
- Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, 14, 247–279. [https://doi.org/10.1016/0010-0285\(82\)90010-X](https://doi.org/10.1016/0010-0285(82)90010-X)
- Moro, S. S., & Steeves, J. K. E. (2018). Normal temporal binding window but no sound-induced flash illusion in people with one eye. *Experimental Brain Research*, 236(6), 1825–1834. <https://doi.org/10.1007/s00221-018-5263-x>
- Narinesingh, C., Goltz, H. C., & Wong, A. M. F. (2017). Temporal binding window of the sound-induced flash illusion in amblyopia. *Investigative Ophthalmology & Visual Science*, 58(3), 1442. <https://doi.org/10.1167/iov.16-21258>
- Putzar, L., Goerendt, I., Lange, K., Rösler, F., & Röder, B. (2007). Early visual deprivation impairs multisensory interactions in humans. *Nature Neuroscience*, 10(10), 1243–1245. <https://doi.org/10.1038/nn1978>
- Rosen, E., Rubowitz, A., & Assia, E. I. (2009). Visual outcome following cataract extraction in patients aged 90 years and older. *Eye*, 23(5), 1120–1124. <https://doi.org/10.1038/eye.2008.203>
- Rudolf, M., Clark, M. E., Chimento, M. F., Li, C.-M., Medeiros, N. E., & Curcio, C. A. (2008). Prevalence and morphology of druse types in the macula and periphery of eyes with age-related maculopathy. *Investigative Ophthalmology & Visual Science*, 49(3), 1200. <https://doi.org/10.1167/iov.07-1466>
- Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). Is inefficient multisensory processing associated with falls in older people? *Experimental Brain Research*, 209(3), 375–384. <https://doi.org/10.1007/s00221-011-2560-z>
- Shams, L., Kamitani, Y., & Shimojo, S. (2000). What you see is what you hear. *Nature*, 408(6814), 788. <https://doi.org/10.1038/35048669>
- Shams, L., Kamitani, Y., & Shimojo, S. (2002). Visual illusion induced by sound. *Cognitive Brain Research*, 14(1), 147–152. [https://doi.org/10.1016/S0926-6410\(02\)00069-1](https://doi.org/10.1016/S0926-6410(02)00069-1)
- Shams, L., Ma, W. J., & Beierholm, U. (2005). Sound-induced flash illusion as an optimal percept. *Neuroreport*, 16(17), 1923–1927. <https://doi.org/10.1097/01.wnr.0000187634.68504.bb>
- Stanford, T. R., & Stein, B. E. (2007). Superadditivity in multisensory integration: Putting the computation in context. *Neuroreport*, 18(8), 787–792. <https://doi.org/10.1097/WNR.0b013e3280c1e315>
- Stapleton, J., Setti, A., Doheny, E. P., Kenny, R. A., & Newell, F. N. (2014). A standing posture is associated with increased susceptibility to the sound-induced flash illusion in fall-prone older adults. *Experimental Brain Research*, 232(2), 423–434. <https://doi.org/10.1007/s00221-013-3750-7>
- Stein, B. E., & Stanford, T. R. (2008). Multisensory integration: Current issues from the perspective of the single neuron. *Nature Reviews Neuroscience*, 9(5), 406. <https://doi.org/10.1038/nrn2377>
- Stevenson, R. A., Altieri, N. A., Kim, S., Pisoni, D. B., & James, T. W. (2010). Neural processing of asynchronous audiovisual speech perception. *Neuroimage*, 49(4), 3308–3318. <https://doi.org/10.1016/j.neuroimage.2009.12.001>
- Stevenson, R. A., Sheffield, S. W., Butera, I. M., Gifford, R. H., & Wallace, M. T. (2017). Multisensory integration in cochlear implant recipients. *Ear and Hearing*, 38(5). <https://doi.org/10.1097/AUD.0000000000000435>
- Stevenson, R. A., Zemtsov, R. K., & Wallace, M. T. (2012). Individual differences in the multisensory temporal binding window predict susceptibility to audiovisual illusions. *Journal of Experimental Psychology: Human Perception and Performance*, 38(6), 1517–1529. <https://doi.org/10.1037/a0027339>
- Stiles, N. R. B., Patel, V. R., & Weiland, J. D. (2019). Auditory-visual interactions in the blind with artificial vision: Are

- multisensory perceptions restored after decades of blindness? *BioRxiv*. <https://doi.org/10.1101/519850>
- Van Atteveldt, N. M., Formisano, E., Blomert, L., & Goebel, R. (2007). The effect of temporal asynchrony on the multisensory integration of letters and speech sounds. *Cerebral Cortex*, 17(4), 962–974. <https://doi.org/10.1093/cercor/bhl007>
- Venezia, J. H., Thurman, S. M., Matchin, W., George, S. E., & Hickok, G. (2016). Timing in audiovisual speech perception: A mini review and new psychophysical data. *Attention, Perception, and Psychophysics*, 78(2), 583–601. <https://doi.org/10.3758/s13414-015-1026-y>
- Votinen, P., Kaarniranta, K., Pääkkönen, A., & Tarkka, I. M. (2017). Visual processing in patients with age-related macular degeneration performing a face detection test. *Clinical Ophthalmology*, 11, 1245–1252. <https://doi.org/10.2147/OPHTH.S132583>
- Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, and Psychophysics*, 72(4), 871–884. <https://doi.org/10.3758/APP.72.4.871>
- van Wassenhove, V., Grant, K. W., & Poeppel, D. (2007). Temporal window of integration in auditory-visual speech perception. *Neuropsychologia*, 45(3), 598–607. <https://doi.org/10.1016/j.neuropsychologia.2006.01.001>
- Whelan, B. J., & Savva, G. M. (2013). Design and methodology of the Irish longitudinal study on ageing. *Journal of the American Geriatrics Society*, 61, 265–268. <https://doi.org/10.1111/jgs.12199>
- Yousefi, S., Sakai, H., Murata, H., Fujino, Y., Matsuura, M., Garway-Heath, D., Weinreb, R., & Asaoka, R. (2018). Rates of visual field loss in primary open-angle glaucoma and primary angle-closure glaucoma: Asymmetric patterns. *Investigative Ophthalmology and Visual Science*, 59(15), 5717–5725. <https://doi.org/10.1167/iovs.18-25140>