

Dual Sensory Impairment and Incident Cardiometabolic Disease: A Multicohort Longitudinal Study

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Abstract

Background To investigate the associations of visual impairment, hearing impairment, and dual sensory impairment (DSI) with incident cardiometabolic disease (CMD) in middle-aged and older adults.

Methods We included 52,912 participants without CMD at baseline from three prospective ageing cohorts: the English Longitudinal Study of Ageing (ELSA), the US Health and Retirement Study (HRS), and the Survey of Health, Ageing and Retirement in Europe (SHARE). All participants had at least two valid assessments. Sensory function, CMD, and covariates were ascertained using standardised cohort questionnaires and assessment protocols. We derived time-updated cumulative average measures of self-reported visual impairment, hearing impairment, and dual sensory impairment (DSI). Cohort-specific associations with incident CMD were estimated using extended Cox proportional hazards models and pooled using random-effects meta-analysis.

Results During 505,421 person-years of follow-up, 14,566 incident CMD events occurred. Higher cumulative average visual impairment, hearing impairment, and DSI were associated with greater CMD risk. Per 1-SD increment in cumulative average DSI, hazard ratios for incident CMD were 1.13 (95% confidence interval [CI], 1.06–1.20) in ELSA, 1.08 (95% CI, 1.05–1.12) in HRS, and 1.11 (95% CI, 1.08–1.13) in SHARE. The pooled hazard ratio was 1.10 (95% CI, 1.08–1.12; $I^2 = 4.7\%$). DSI was also associated with incident heart disease, diabetes, and stroke. Findings were similar in the 2-year lag analysis.

Conclusions Higher time-updated cumulative average levels of visual impairment, hearing impairment, and DSI were associated with increased risk of incident CMD. Associations were most consistent for DSI, suggesting that combined assessment of visual and hearing function may complement conventional cardiometabolic risk assessment.

Introduction

Cardiometabolic disease (CMD), defined here as heart disease, diabetes, or stroke, is a leading cause of death, disability, and health-care use among middle-aged and older adults [1–4]. As populations age, prevention efforts must extend beyond conventional risk factors, such as blood pressure, glycaemia, lipids, and body weight, to markers of overall health, functional reserve, and long-term risk [5, 6]. Functional changes that are readily detected in community and clinical settings could therefore complement conventional cardiometabolic risk assessment.

Visual and hearing impairment are common in later life and become more prevalent with age [7–10]. Beyond restricting activities of daily living, social participation, and independent living, sensory impairment can limit access to health information and impede chronic disease self-management [11–15], with adverse consequences for health behaviours and metabolic risk-factor control. Sensory impairment may also share underlying pathways with vascular injury, inflammation, metabolic dysfunction, neurodegeneration, and broader physiological vulnerability [16–19].

Previous studies have linked visual or hearing impairment to cardiovascular disease, diabetes, stroke, and mortality [20–28]. However, most have examined a single sensory domain, and few have compared visual impairment, hearing impairment, and DSI across multiple cohorts [23–27]. Reliance on a single baseline assessment also precludes evaluation of changes in sensory function and cumulative exposure over time. Whether these associations are consistent across countries and individual CMD outcomes remains uncertain.

DSI, the concurrent impairment of vision and hearing, may reflect more profound functional loss and physiological vulnerability than either impairment alone, but its association with subsequent CMD is poorly understood. We therefore used data from three large ageing cohorts—the English Longitudinal Study of Ageing (ELSA), the US Health and Retirement Study (HRS), and the Survey of Health, Ageing and Retirement in Europe (SHARE)—to examine visual impairment, hearing impairment, and DSI in relation to incident CMD and its components, including heart disease, diabetes, and stroke. We aimed to assess whether sensory function could contribute to cardiometabolic risk assessment in middle-aged and older adults.

Because sensory function can change with ageing, disease progression, and health behaviours, we used repeated assessments to derive time-updated cumulative average exposure measures. This approach captures long-term sensory status more fully than a single baseline measure and reduces sensitivity to measurement error and short-term fluctuation.

Methods

Study design and participants

Data were drawn from three large longitudinal ageing cohorts: the English Longitudinal Study of Ageing (ELSA), the US Health and Retirement Study (HRS), and the Survey of Health, Ageing and Retirement in Europe (SHARE). Participating countries and regions are listed in Supplementary Table S1. The study designs, sampling strategies, and follow-up procedures of these cohorts have been described previously [29–32].

This study was a secondary analysis of existing cohort data. No study-specific questionnaire or questionnaire guide was developed or administered for the present study. Information on sensory impairment, cardiometabolic diseases, and covariates was obtained from the Harmonized ELSA and the RAND HRS Longitudinal File and Harmonized SHARE datasets (Supplementary Table S2), which harmonise information collected through the standardised questionnaires and assessment protocols of the respective cohorts [33–35].

We analysed ELSA waves 1–9 (2002–2019), HRS waves 3–15 (1996–2020), and SHARE waves 4–9 (2010–2022) (Supplementary Table S3). Because cumulative average sensory impairment was derived from repeated measurements, participants were required to have at least two valid survey observations.

For the primary analysis, participants with heart disease, diabetes, or stroke at baseline were excluded. Incident CMD was defined as the first occurrence of any of these conditions during follow-up, consistent with previous multicohort studies [36]. Heart disease, diabetes, and stroke were also examined separately. For each outcome-specific analysis, participants with the corresponding condition at baseline were excluded.

For each analysis, baseline was defined as the first eligible survey wave at which participants had complete information on outcome status, sensory function, and covariates and contributed at least one valid risk interval. Participants with missing baseline information or no valid risk interval were excluded. The primary CMD analysis included 3,631 participants from ELSA, 12,064 from HRS, and 37,217 from SHARE. Cohort-specific participant selection is shown in Supplementary Figure S1.

Assessment of sensory impairment and construction of time-updated cumulative average exposure

Sensory function was assessed using self-reported indicators of distance vision, near vision, and hearing. In HRS, vision and hearing were rated as “poor,” “fair,” “good,” “very good,” or “excellent,” with higher original response values indicating better sensory function. In ELSA and SHARE, vision was rated as “excellent,” “very good,” “good,” “fair,” “poor,” or “blind,” whereas hearing was rated as “excellent,” “very good,” “good,” “fair,” or “poor”; higher original response values indicated poorer sensory function. To ensure comparability across cohorts, all measures were recoded so that higher values consistently indicated poorer sensory function. Detailed variable definitions, response categories, and harmonisation procedures are presented in Supplementary Table S4.

To harmonise sensory scores across cohorts [37], responses for vision and hearing were recoded on a 0–4 scale, with 0 denoting the best and 4 the worst function. “Excellent,” “very good,” “good,” “fair,” and “poor” were assigned scores of 0, 1, 2, 3, and 4, respectively. Because HRS used the opposite scoring direction, its scores were reverse-coded. ELSA and SHARE responses were recoded directly, and participants who reported being “blind” received a score of 4 for the relevant vision item. The visual impairment score was the sum of distance- and near-vision scores (range 0–8). The hearing impairment score was based on self-reported hearing (range 0–4). The DSI score was the sum of the visual and hearing impairment scores (range 0–12). Higher scores indicated greater impairment.

To characterise long-term sensory impairment during follow-up, we derived time-updated cumulative average scores for visual impairment, hearing impairment, and DSI. At each wave, the cumulative average included all non-missing measurements obtained from baseline through that wave. Exposure for each risk interval was the cumulative average through the wave immediately preceding the interval, thereby introducing a one-wave lag. For the interval in which an outcome was first reported, exposure therefore incorporated only assessments made before that interval; sensory data collected at the event wave were not used. The event interval was retained, and subsequent intervals were removed from the risk set. For participants without an event, exposure was updated through the final eligible interval. Higher cumulative average scores denoted more severe long-term impairment. Because questionnaire wording, survey frequency, and follow-up intervals differed across cohorts, analyses were conducted separately in each cohort before effect estimates were pooled by random-effects meta-analysis.

Outcome ascertainment

The primary outcome was incident CMD, defined as the first report of heart disease, diabetes, or stroke during follow-up. Each component was also analysed separately. Information on heart disease, diabetes, and stroke was obtained from self-reported physician diagnoses collected through the standardised questionnaires of ELSA, HRS, and SHARE (Supplementary Table S4). Across cohorts, participants were asked whether they had ever been diagnosed with heart disease, diabetes, or stroke by a physician. Responses were coded as no (0) or yes (1).

For the primary CMD analysis, follow-up extended from the participant-specific baseline to the first report of heart disease, diabetes, or stroke, or to the last eligible assessment, whichever occurred first. For the outcome-specific analyses, the wave at which the corresponding condition was first reported was designated the event wave. Only participants without that condition at baseline were included. Because outcomes were assessed at discrete survey waves, event time was assigned to the interview date on which the diagnosis was first reported.

Covariates

Potential confounders were selected a priori based on previous literature and the social determinants of health framework [38]. Baseline covariates were obtained from the standardised questionnaires and assessment protocols of ELSA, HRS, and SHARE and included demographic and socioeconomic characteristics, health behaviours, cognitive function, and chronic conditions (Supplementary Table S5).

Demographic and socioeconomic covariates included age (< 65 or ≥ 65 years), sex, marital status (married or cohabiting vs other), educational attainment (below secondary school, secondary or vocational education, or university and above), and household wealth (quartiles). Health behaviours included smoking (never vs ever or current), alcohol consumption (never vs ever or current), and physical activity (active vs inactive).

Chronic conditions were based on self-reported physician diagnoses of lung disease, hypertension, hypercholesterolaemia, cancer, arthritis, and memory-related disorders. Cognitive function comprised orientation, calculation, and memory. Orientation was assessed from the year, month, and day; calculation from serial subtraction by 7 (SER7); and memory from cohort-specific standardised tests. Higher scores indicated better cognitive performance. All covariates were measured at the participant-specific baseline and entered as baseline covariates in the multivariable extended Cox models.

Statistical analysis

Continuous variables are reported as means (SDs) and categorical variables as numbers (%). For each outcome, follow-up was calculated from the person-time contributed by each participant and expressed in person-years. Extended Cox proportional hazards models were used to estimate associations between time-updated cumulative average sensory impairment and incident CMD, heart disease, diabetes, and stroke, with sensory impairment modelled as a time-varying exposure [39–42]. Risk intervals were defined by the elapsed time between consecutive survey waves. For each participant, interval *k* extended from wave *k*-1 to wave *k*.

Within each interval, exposure was the cumulative average of measurements obtained at the start of that interval and all preceding waves, yielding a one-wave lag relative to outcome ascertainment. Event intervals were retained, but exposure was based only on sensory assessments preceding the first report of the outcome. All post-event intervals were excluded.

Cumulative average visual impairment and DSI were categorised into cohort-specific quartiles, with the lowest quartile (Q1) as the reference. Given its distribution, cumulative average hearing impairment was categorised into cohort-specific tertiles, with the lowest tertile as the reference. Hazard ratios (HRs) and 95% confidence intervals (CIs) were estimated for each category. Linear trends were tested by entering the ordered category as a continuous variable. Cumulative average visual impairment, hearing impairment, and DSI were also standardised within each cohort to estimate associations per 1-SD increment. The proportional hazards assumption was evaluated by testing interactions between each exposure and follow-up time. Restricted cubic splines were incorporated into the Cox models to assess potential nonlinear dose–response associations of cumulative average visual impairment, hearing impairment, and DSI with CMD and its components [43, 44]. Nonlinearity was evaluated from the *P* value for the nonlinear spline terms. All models were adjusted for age, sex, educational attainment, marital status, smoking, alcohol consumption, physical activity, cognitive function, household wealth, and chronic conditions at baseline.

Analyses were conducted separately in ELSA, HRS, and SHARE. Cohort-specific regression coefficients and standard errors were pooled using a DerSimonian–Laird random-effects meta-analysis to obtain summary HRs and 95% CIs. Between-cohort heterogeneity was assessed with Cochran's *Q*, *I*², and *τ*² [45–47].

We examined effect modification by age (< 65 vs ≥ 65 years), sex, educational attainment, marital status, and household wealth. Subgroup estimates were interpreted alongside formal tests for interaction. To address potential reverse causation, we performed a 2-year lag analysis in addition to excluding participants with the corresponding outcome at baseline. The first 2 years after baseline were excluded from person-time at risk, and participants who first reported the outcome during this period were excluded. Participants followed for more than 2 years entered the risk set 2 years after baseline. Associations were re-estimated using the models applied in the primary analysis. The lag analysis was intended to reduce the influence of CMD or its precursors that might have been present but unreported or undiagnosed at baseline. All tests were two-sided, with *P* < 0.05 considered statistically significant.

Results

Participant characteristics

The primary analysis included 3,631 participants from ELSA, 12,064 from HRS, and 37,217 from SHARE. Mean follow-up was 13.30, 14.16, and 8.88 years, respectively. Participants younger than 65 years comprised 73.2% of ELSA, 66.9% of HRS, and 60.1% of SHARE; the corresponding proportions of men were 43.1%, 37.4%, and 42.3%. Baseline characteristics and sensory impairment scores are shown in Table 1.

Table 1. Baseline characteristics of participants in ELSA, HRS, and SHARE

Characteristics	ELSA (n = 3,631)	HRS (n = 12,064)	SHARE (n = 37,217)
Follow-up duration, y	13.30 (4.99)	14.16 (7.01)	8.88 (2.97)
Age			
<65	2,657 (73.2)	8,075 (66.9)	22,365 (60.1)
≥65	974 (26.8)	3,989 (33.1)	14,852 (39.9)
Sex			
Male	1,566 (43.1)	4,510 (37.4)	15,733 (42.3)
Female	2,065 (56.9)	7,554 (62.6)	21,484 (57.7)
Marital status			
Married or live together	2,822 (77.7)	8,978 (74.4)	29,053 (78.1)
Others	809 (22.3)	3,086 (25.6)	8,164 (21.9)
Education level			
Low	1,065 (29.3)	2,700 (22.4)	12,387 (33.3)
Middle	1,896 (52.2)	4,473 (37.1)	15,212 (40.9)
High	670 (18.5)	4,891 (40.5)	9,618 (25.8)
Smoking status			
Never	1,465 (40.3)	5,202 (43.1)	19,918 (53.5)
Ever or current	2,166 (59.7)	6,862 (56.9)	17,299 (46.5)
Alcohol consumption			
Never	247 (6.8)	5,332 (44.2)	3,876 (10.4)
Ever or current	3,384 (93.2)	6,732 (55.8)	33,341 (89.6)
Physical activity			
Active	3,321 (91.5)	9,718 (80.6)	35,030 (94.1)
Inactive	310 (8.5)	2,346 (19.4)	2,187 (5.9)
Cognitive score	14.07 (2.40)	13.36 (2.84)	13.78 (2.44)
Household wealth			
Q1	668 (18.4)	3,469 (28.8)	9,091 (24.4)
Q2	1,213 (33.4)	3,422 (28.4)	8,593 (23.1)
Q3	1,082 (29.8)	2,564 (21.3)	9,582 (25.7)
Q4	668 (18.4)	2,609 (21.6)	9,951 (26.7)
Chronic diseases			
Lung disease	101 (2.8)	378 (3.1)	1,945 (5.2)
Hypertension	975 (26.9)	3,802 (31.5)	12,362 (33.2)
High cholesterol	559 (15.4)	8,387 (69.5)	7,651 (20.6)
Cancer	143 (3.9)	793 (6.6)	2,431 (6.5)
Arthritis	873 (24.0)	4,628 (38.4)	8,367 (22.5)
Memory disease	4 (0.1)	88 (0.7)	157 (0.4)
Mean visual impairment score	2.33 (1.69)	2.93 (1.77)	3.01 (1.88)
Mean hearing impairment score	1.38 (1.09)	1.36 (1.05)	1.52 (1.01)

Characteristics	ELSA (n = 3,631)	HRS (n = 12,064)	SHARE (n = 37,217)
Mean DSI score	3.70 (2.23)	4.29 (2.32)	4.53 (2.40)

Note: Values are n (%) or mean (SD). Baseline was the first wave at which a participant met the eligibility criteria for the primary analysis. Follow-up was calculated from baseline to incident CMD or censoring.

Associations of time-updated cumulative average sensory impairment with incident CMD

During 48,232 person-years in ELSA, 164,230 person-years in HRS, and 292,959 person-years in SHARE, 1,159, 5,811, and 7,596 incident CMD events occurred, respectively. Compared with the lowest quartile of cumulative average visual impairment, the highest quartile was associated with greater CMD risk in ELSA (HR 1.49, 95% CI 1.17–1.90), HRS (1.18, 1.08–1.28), and SHARE (1.23, 1.15–1.31). Compared with the lowest tertile of cumulative average hearing impairment, the highest tertile was also associated with greater CMD risk in ELSA (HR 1.23, 95% CI 1.06–1.43), HRS (1.18, 1.10–1.27), and SHARE (1.15, 1.08–1.23).

Cumulative average DSI was positively associated with incident CMD. Per 1-SD increment, HRs were 1.13 (95% CI 1.06–1.20) in ELSA, 1.08 (1.05–1.12) in HRS, and 1.11 (1.08–1.13) in SHARE (Table 2). Restricted cubic spline analyses supported a dose–response association between cumulative average DSI and incident CMD (Figure 1). Associations of DSI with incident CMD, heart disease, diabetes, and stroke are shown in Supplementary Figure S2.

Table 2. Associations of time-updated cumulative average sensory impairment with incident cardiometabolic disease in ELSA, HRS, and SHARE

Sensory impairment	ELSA (1,159/48,232)			HRS (5,811/164,230)			SHARE (7,596/292,959)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Cumulative average visual impairment									
Quartile 1	163/8,739	Reference	-	1,406/48,878	Reference	-	2,322/108,161	Reference	-
Quartile 2	282/13,269	1.06 (0.87-1.28)	0.578	1,454/40,854	1.09 (1.01-1.17)	0.030	1,316/56,643	1.05 (0.98-1.12)	0.202
Quartile 3	586/22,590	1.19 (0.99-1.42)	0.057	1,795/47,708	1.12 (1.04-1.20)	0.003	2,198/76,212	1.19 (1.12-1.26)	<0.001
Quartile 4	128/3,634	1.49 (1.17-1.90)	0.001	1,156/26,790	1.18 (1.08-1.28)	<0.001	1,760/51,943	1.23 (1.15-1.31)	<0.001
Test for linear trend	-	1.13 (1.05-1.21)	<0.001	-	1.05 (1.03-1.08)	<0.001	-	1.08 (1.05-1.10)	<0.001
Per SD increment	-	1.11 (1.05-1.18)	<0.001	-	1.07 (1.04-1.10)	<0.001	-	1.10 (1.07-1.12)	<0.001
Cumulative average hearing impairment									
Tertile 1	402/19,838	Reference	-	1,961/67,726	Reference	-	2,417/117,168	Reference	-
Tertile 2	411/17,892	0.98 (0.86-1.13)	0.828	2,323/63,146	1.07 (1.01-1.14)	0.032	3,314/121,759	1.11 (1.05-1.17)	<0.001
Tertile 3	346/10,502	1.23 (1.06-1.43)	0.008	1,527/33,358	1.18 (1.10-1.27)	<0.001	1,865/54,032	1.15 (1.08-1.23)	<0.001
Test for linear trend	-	1.11 (1.02-1.19)	0.011	-	1.09 (1.05-1.13)	<0.001	-	1.08 (1.04-1.11)	<0.001
Per SD increment	-	1.09 (1.02-1.15)	0.007	-	1.06 (1.03-1.09)	<0.001	-	1.07 (1.05-1.10)	<0.001
Cumulative average DSI									
Quartile 1	159/9,251	Reference	-	1,196/44,704	Reference	-	1,748/89,064	Reference	-
Quartile 2	389/18,438	1.10 (0.91-1.33)	0.312	1,018/30,350	1.11 (1.02-1.21)	0.018	2,349/97,030	1.12 (1.05-1.19)	<0.001
Quartile 3	247/9,292	1.24 (1.01-1.53)	0.036	2,337/61,092	1.17 (1.09-1.25)	<0.001	1,501/53,353	1.18 (1.10-1.27)	<0.001
Quartile 4	364/11,251	1.44 (1.19-1.75)	<0.001	1,260/28,084	1.24 (1.14-1.35)	<0.001	1,998/53,512	1.33 (1.24-1.42)	<0.001
Test for linear trend	-	1.13 (1.07-1.20)	<0.001	-	1.07 (1.04-1.10)	<0.001	-	1.09 (1.07-1.12)	<0.001

Sensory impairment	ELSA (1,159/48,232)			HRS (5,811/164,230)			SHARE (7,596/292,959)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Per SD increment	-	1.13 (1.06-1.20)	<0.001	-	1.08 (1.05-1.12)	<0.001	-	1.11 (1.08-1.13)	<0.001

Note: HRs and 95% CIs were estimated using Cox proportional hazards models adjusted for age, sex, educational attainment, marital status, smoking, alcohol consumption, physical activity, cognitive function, household wealth, and baseline lung disease, hypertension, hypercholesterolaemia, cancer, arthritis, and memory-related disorders, where available. Person-years were calculated as the sum of tstop – tstart across risk intervals. Continuous estimates are per 1-SD increment in standardised cumulative average exposure. Dashes indicate not applicable.

Associations of time-updated cumulative average sensory impairment with incident heart disease

Incident heart disease occurred in 796 participants in ELSA, 3,701 in HRS, and 4,401 in SHARE. Per 1-SD increment in cumulative average visual impairment, HRs for incident heart disease were 1.06 (95% CI 0.98–1.14) in ELSA, 1.07 (1.03–1.11) in HRS, and 1.11 (1.08–1.15) in SHARE. Per 1-SD increment in cumulative average hearing impairment, HRs for incident heart disease were 1.15 (95% CI 1.06–1.23) in ELSA, 1.08 (1.04–1.12) in HRS, and 1.11 (1.08–1.15) in SHARE (Supplementary Figure S3).

Cumulative average DSI was positively associated with incident heart disease. Per 1-SD increment, HRs were 1.12 (95% CI 1.04–1.20) in ELSA, 1.09 (1.05–1.13) in HRS, and 1.14 (1.11–1.18) in SHARE (Table 3). Restricted cubic spline analyses indicated nonlinear associations between cumulative average DSI and incident heart disease (P for nonlinearity = 0.002 in ELSA and <0.001 in HRS and SHARE; Figures 2–4).

Table 3. Associations of time-updated cumulative average sensory impairment with incident heart disease in ELSA, HRS, and SHARE

Sensory impairment	ELSA (796/51,516)			HRS (3,701/186,942)			SHARE (4,401/307,317)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Cumulative average visual impairment									
Quartile 1	113/9,019	Reference	-	824/52,640	Reference	-	1,298/111,812	Reference	-
Quartile 2	192/13,959	0.96 (0.76-1.21)	0.710	948/46,424	1.14 (1.03-1.25)	0.009	747/59,986	1.02 (0.93-1.12)	0.674
Quartile 3	406/24,426	1.04 (0.84-1.29)	0.712	1,168/55,422	1.16 (1.05-1.27)	0.002	1,288/80,194	1.24 (1.14-1.34)	<0.001
Quartile 4	85/4,112	1.20 (0.89-1.61)	0.229	761/32,456	1.22 (1.10-1.36)	<0.001	1,068/55,325	1.30 (1.19-1.41)	<0.001
Test for linear trend	-	1.06 (0.97-1.15)	0.198	-	1.06 (1.03-1.10)	<0.001	-	1.10 (1.07-1.13)	<0.001
Per SD increment	-	1.06 (0.98-1.14)	0.139	-	1.07 (1.03-1.11)	<0.001	-	1.11 (1.08-1.15)	<0.001
Cumulative average hearing impairment									
Tertile 1	257/20,813	Reference	-	1,157/73,734	Reference	-	1,294/120,892	Reference	-
Tertile 2	273/19,310	0.94 (0.79-1.12)	0.498	1,465/73,346	1.04 (0.96-1.13)	0.335	1,913/128,789	1.14 (1.06-1.23)	<0.001
Tertile 3	266/11,393	1.34 (1.11-1.60)	0.002	1,079/39,862	1.22 (1.11-1.33)	<0.001	1,194/57,636	1.26 (1.16-1.37)	<0.001
Test for linear trend	-	1.16 (1.05-1.27)	0.002	-	1.10 (1.05-1.15)	<0.001	-	1.12 (1.08-1.17)	<0.001
Per SD increment	-	1.15 (1.06-1.23)	<0.001	-	1.08 (1.04-1.12)	<0.001	-	1.11 (1.08-1.15)	<0.001
Cumulative average DSI									
Quartile 1	111/9,542	Reference	-	709/48,096	Reference	-	961/91,828	Reference	-
Quartile 2	247/19,597	0.91 (0.72-1.14)	0.410	615/33,836	1.07 (0.96-1.20)	0.209	1,330/102,097	1.11 (1.02-1.21)	0.012
Quartile 3	185/10,054	1.16 (0.91-1.48)	0.228	1,514/71,144	1.16 (1.05-1.27)	0.002	872/56,300	1.22 (1.11-1.34)	<0.001
Quartile 4	253/12,323	1.24 (0.98-1.57)	0.069	863/33,866	1.28 (1.15-1.43)	<0.001	1,238/57,092	1.42 (1.30-1.55)	<0.001
Test for linear trend	-	1.12 (1.04-1.20)	0.002	-	1.08 (1.05-1.12)	<0.001	-	1.12 (1.09-1.15)	<0.001

Sensory impairment	ELSA (796/51,516)			HRS (3,701/186,942)			SHARE (4,401/307,317)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Per SD increment	-	1.12 (1.04-1.20)	0.003	-	1.09 (1.05-1.13)	<0.001	-	1.14 (1.11-1.18)	<0.001

Note: HRs and 95% CIs were estimated using Cox proportional hazards models adjusted for age, sex, educational attainment, marital status, smoking, alcohol consumption, physical activity, cognitive function, household wealth, and baseline lung disease, hypertension, hypercholesterolaemia, cancer, arthritis, and memory-related disorders, where available. Person-years were calculated as the sum of tstop – tstart across risk intervals. Continuous estimates are per 1-SD increment in standardised cumulative average exposure. Dashes indicate not applicable.

Associations of time-updated cumulative average sensory impairment with incident diabetes

Incident diabetes occurred in 390 participants in ELSA, 2,437 in HRS, and 2,858 in SHARE. Per 1-SD increment in cumulative average visual impairment, HRs for incident diabetes were 1.13 (95% CI 1.02–1.24) in ELSA, 1.08 (1.03–1.13) in HRS, and 1.07 (1.03–1.11) in SHARE. Per 1-SD increment in cumulative average hearing impairment, HRs for incident diabetes were 1.06 (95% CI 0.96–1.17) in ELSA, 1.07 (1.02–1.11) in HRS, and 1.02 (0.98–1.06) in SHARE.

Cumulative average DSI was positively associated with incident diabetes. Per 1-SD increment, HRs were 1.12 (95% CI 1.02–1.25) in ELSA, 1.09 (1.05–1.14) in HRS, and 1.06 (1.02–1.10) in SHARE (Table 4). Restricted cubic spline analyses indicated nonlinear associations between cumulative average DSI and incident diabetes across all three cohorts (Figures 2–4).

Table 4. Associations of time-updated cumulative average sensory impairment with incident diabetes in ELSA, HRS, and SHARE

Sensory impairment	ELSA (390/53,494)			HRS (2,437/193,478)			SHARE (2,858/313,781)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Cumulative average visual impairment									
Quartile 1	52/9,258	Reference	-	577/54,292	Reference	-	865/112,995	Reference	-
Quartile 2	89/14,507	1.10 (0.78-1.55)	0.583	566/48,434	1.00 (0.89-1.13)	0.971	504/61,298	1.03 (0.92-1.15)	0.590
Quartile 3	204/25,344	1.38 (1.01-1.89)	0.045	784/57,044	1.12 (1.00-1.25)	0.048	850/82,064	1.15 (1.04-1.27)	0.005
Quartile 4	45/4,385	1.57 (1.04-2.38)	0.032	510/33,708	1.13 (0.99-1.29)	0.062	639/57,424	1.10 (0.99-1.23)	0.070
Test for linear trend	-	1.18 (1.05-1.33)	0.007	-	1.05 (1.01-1.10)	0.016	-	1.04 (1.01-1.08)	0.013
Per SD increment	-	1.13 (1.02-1.24)	0.019	-	1.08 (1.03-1.13)	<0.001	-	1.07 (1.03-1.11)	<0.001
Cumulative average hearing impairment									
Tertile 1	134/21,364	Reference	-	818/75,706	Reference	-	949/121,851	Reference	-
Tertile 2	154/19,798	1.22 (0.96-1.54)	0.104	989/74,704	1.12 (1.02-1.23)	0.018	1,295/131,130	1.12 (1.03-1.22)	0.008
Tertile 3	102/12,332	1.17 (0.89-1.54)	0.255	630/43,068	1.18 (1.05-1.32)	0.004	614/60,800	1.01 (0.91-1.12)	0.888
Test for linear trend	-	1.09 (0.95-1.24)	0.210	-	1.09 (1.03-1.15)	0.003	-	1.01 (0.96-1.07)	0.585
Per SD increment	-	1.06 (0.96-1.17)	0.275	-	1.07 (1.02-1.11)	0.003	-	1.02 (0.98-1.06)	0.346
Cumulative average DSI									
Quartile 1	48/9,812	Reference	-	471/49,240	Reference	-	669/92,497	Reference	-
Quartile 2	137/20,185	1.37 (0.98-1.90)	0.067	433/35,384	1.18 (1.03-1.34)	0.017	917/103,880	1.12 (1.01-1.24)	0.027
Quartile 3	79/10,391	1.44 (1.00-2.08)	0.050	985/73,100	1.23 (1.10-1.38)	<0.001	582/57,714	1.13 (1.01-1.26)	0.037
Quartile 4	126/13,106	1.72 (1.22-2.43)	0.002	548/35,754	1.29 (1.13-1.47)	<0.001	690/59,690	1.14 (1.02-1.28)	0.019
Test for linear trend	-	1.16 (1.05-1.28)	0.003	-	1.08 (1.04-1.13)	<0.001	-	1.04 (1.00-1.08)	0.027

Sensory impairment	ELSA (390/53,494)			HRS (2,437/193,478)			SHARE (2,858/313,781)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Per SD increment	-	1.12 (1.02-1.25)	0.025	-	1.09 (1.05-1.14)	<0.001	-	1.06 (1.02-1.10)	0.002

Note: HRs and 95% CIs were estimated using Cox proportional hazards models adjusted for age, sex, educational attainment, marital status, smoking, alcohol consumption, physical activity, cognitive function, household wealth, and baseline lung disease, hypertension, hypercholesterolaemia, cancer, arthritis, and memory-related disorders, where available. Person-years were calculated as the sum of tstop – tstart across risk intervals. Continuous estimates are per 1-SD increment in standardised cumulative average exposure. Dashes indicate not applicable.

Associations of time-updated cumulative average sensory impairment with incident stroke

Incident stroke occurred in 187 participants in ELSA, 1,581 in HRS, and 1,682 in SHARE. Per 1-SD increment in cumulative average visual impairment, HRs for incident stroke were 1.22 (95% CI 1.06–1.41) in ELSA, 1.06 (1.01–1.12) in HRS, and 1.08 (1.03–1.13) in SHARE. Per 1-SD increment in cumulative average hearing impairment, HRs for incident stroke were 1.06 (95% CI 0.91–1.23) in ELSA, 1.02 (0.97–1.08) in HRS, and 1.03 (0.98–1.08) in SHARE.

Cumulative average DSI was positively associated with incident stroke. Per 1-SD increment, HRs were 1.20 (95% CI 1.03–1.39) in ELSA, 1.06 (1.00–1.12) in HRS, and 1.08 (1.02–1.13) in SHARE (Table 5). Restricted cubic spline analyses indicated nonlinear associations of cumulative average visual impairment and DSI with incident stroke across cohorts (Figures 2–4).

Table 5. Associations of time-updated cumulative average sensory impairment with incident stroke in ELSA, HRS, and SHARE

Sensory impairment	ELSA (187/55,252)			HRS (1,581/205,298)			SHARE (1,682/319,535)		
	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value	Cases/person-years	HR (95% CI)	P value
Cumulative average visual impairment									
Quartile 1	19/9,437	Reference	-	308/56,484	Reference	-	496/114,398	Reference	-
Quartile 2	44/14,872	1.29 (0.75-2.22)	0.356	423/51,160	1.21 (1.05-1.41)	0.011	316/62,588	1.08 (0.93-1.24)	0.315
Quartile 3	93/26,400	1.31 (0.79-2.19)	0.291	476/61,334	1.07 (0.92-1.24)	0.389	437/83,803	1.03 (0.90-1.17)	0.672
Quartile 4	31/4,543	2.17 (1.19-3.95)	0.011	374/36,320	1.21 (1.03-1.43)	0.023	433/58,746	1.24 (1.08-1.42)	0.002
Test for linear trend	-	1.23 (1.02-1.48)	0.028	-	1.04 (0.99-1.09)	0.147	-	1.06 (1.02-1.11)	0.009
Per SD increment	-	1.22 (1.06-1.41)	0.006	-	1.06 (1.01-1.12)	0.029	-	1.08 (1.03-1.13)	0.002
Cumulative average hearing impairment									
Tertile 1	57/21,914	Reference	-	462/78,768	Reference	-	515/123,387	Reference	-
Tertile 2	65/20,653	0.91 (0.63-1.32)	0.631	651/80,074	1.06 (0.93-1.19)	0.389	690/134,303	0.97 (0.86-1.09)	0.594
Tertile 3	65/12,685	1.14 (0.78-1.67)	0.506	468/46,456	1.08 (0.94-1.24)	0.261	477/61,845	1.10 (0.96-1.25)	0.176
Test for linear trend	-	1.07 (0.88-1.30)	0.486	-	1.04 (0.97-1.11)	0.260	-	1.05 (0.98-1.12)	0.195
Per SD increment	-	1.06 (0.91-1.23)	0.479	-	1.02 (0.97-1.08)	0.377	-	1.03 (0.98-1.08)	0.252
Cumulative average DSI									
Quartile 1	18/10,002	Reference	-	268/51,308	Reference	-	367/93,705	Reference	-
Quartile 2	61/20,874	1.28 (0.75-2.19)	0.360	262/36,926	1.10 (0.93-1.31)	0.262	510/105,912	1.06 (0.93-1.22)	0.366
Quartile 3	34/10,844	1.17 (0.65-2.10)	0.607	654/78,536	1.12 (0.97-1.30)	0.126	310/59,013	1.05 (0.90-1.23)	0.510
Quartile 4	74/13,532	1.76 (1.03-3.02)	0.039	397/38,528	1.16 (0.98-1.37)	0.086	495/60,905	1.31 (1.13-1.51)	<0.001
Test for linear trend	-	1.18 (1.02-1.37)	0.024	-	1.05 (0.99-1.10)	0.094	-	1.09 (1.04-1.14)	<0.001
Per SD increment	-	1.20 (1.03-1.39)	0.017	-	1.06 (1.00-1.12)	0.045	-	1.08 (1.02-1.13)	0.004

Note: HRs and 95% CIs were estimated using Cox proportional hazards models adjusted for age, sex, educational attainment, marital status, smoking, alcohol consumption, physical activity, cognitive function, household wealth, and baseline lung disease, hypertension, hypercholesterolaemia, cancer, arthritis, and memory-related disorders, where available. Person-years were calculated as the sum of $t_{\text{stop}} - t_{\text{start}}$ across risk intervals. Continuous estimates are per 1-SD increment in standardised cumulative average exposure. Dashes indicate not applicable.

Meta-analysis

In random-effects meta-analysis, each 1-SD increment in cumulative average DSI was associated with a 10% greater risk of incident CMD (HR 1.10, 95% CI 1.08–1.12). Positive associations were also observed for heart disease, diabetes, and stroke. Between-cohort heterogeneity was low for CMD ($I^2 = 4.7\%$), diabetes (0.0%), and stroke (14.9%) and moderate for heart disease (41.2%). (Supplementary Table S6)

Subgroup analyses

Associations between cumulative average DSI and incident CMD were directionally consistent across subgroups defined by age, sex, educational attainment, marital status, and household wealth. Effect estimates varied in magnitude, but no subgroup showed a clear reversal of the association (Supplementary Table S7–Figure S4–S6).

Sensitivity analyses

After participants who first reported the corresponding outcome within 2 years of baseline were excluded, associations of cumulative average visual impairment, hearing impairment, and DSI with incident CMD were similar to those in the primary analysis, and most remained statistically significant. In random-effects meta-analysis of the 2-year lag results, each 1-SD increment in cumulative average DSI remained associated with incident CMD (HR 1.11, 95% CI 1.08–1.14; $P < 0.001$). Associations with heart disease, diabetes, and stroke also remained statistically significant, and effect estimates differed little from those in the primary analysis (Supplementary Table S8–S9–Figure S7–S8).

Discussion

Principal findings

In three large ageing cohorts, we examined time-updated cumulative average visual impairment, hearing impairment, and DSI in relation to incident CMD and its components.

Across cohorts, greater visual impairment, hearing impairment, and DSI were associated with higher CMD risk. Associations with visual impairment were most consistent for CMD, diabetes, and stroke, whereas those with hearing impairment were most consistent for CMD and heart disease. DSI was consistently associated with CMD and each of its components. The pooled estimate indicated a 10% greater risk of CMD per 1-SD increment in cumulative average DSI. Restricted cubic spline analyses suggested dose–response associations, some of which were nonlinear. The direction of association was broadly consistent across cohorts and major sociodemographic subgroups. These findings identify DSI as a potential marker of cardiometabolic risk in middle-aged and older adults.

Interpretation and potential mechanisms

Visual and hearing impairment have previously been associated with cardiovascular disease, diabetes, stroke, functional limitations, and all-cause mortality [20–28]. Our findings extend this evidence across cohorts in the UK, the US, and continental Europe by incorporating repeated assessments of visual impairment, hearing impairment, and DSI. Associations were evident for incident CMD, although their magnitude and consistency differed across individual components.

Greater cumulative average visual impairment was associated with CMD, diabetes, and stroke, consistent with previous evidence. Loss of vision can impede access to health information and health care, reduce physical activity, and compromise chronic disease self-management. These consequences could hinder long-term control of body weight, blood pressure, and glycaemia [10, 49, 50]. Retinal vascular changes can reflect systemic vascular injury and inflammation. Chronic hyperglycaemia damages the retinal microvasculature through several pathways; persistent visual impairment might therefore signal unrecognised dysglycaemia or prolonged hyperglycaemic exposure [51, 52]. The retinal and cerebral microcirculations also share developmental, structural, and regulatory features, and retinal microvascular abnormalities have been associated with cerebral small-vessel disease and subsequent stroke [53].

The comparatively consistent associations of hearing impairment with CMD and heart disease may reflect shared vascular and metabolic mechanisms. Hearing loss commonly coexists with hypertension, diabetes, dyslipidaemia, and smoking [54], and may therefore serve as an indicator of cumulative vascular and metabolic injury. Age-related vascular changes in the inner ear and impaired cochlear microcirculation can damage auditory nerve function [55, 56]. Hearing impairment might also affect cardiometabolic health indirectly by limiting social

participation and physical activity and complicating self-care [9]. Unlike impairment in a single sensory domain, DSI captures concurrent deficits in vision and hearing and may indicate a greater loss of functional reserve and more extensive multisystem impairment [11, 12, 57]. Its associations with CMD and each component were more consistent than those for either sensory domain alone. This pattern accords with evidence linking DSI to functional limitation, multimorbidity, and adverse ageing outcomes.

DSI can hinder communication with health-care professionals, disease monitoring, medication adherence, physical activity, and social participation. It might also represent the combined expression of vascular injury, metabolic dysfunction, inflammation, and declining physiological reserve.

Strengths

This study combined three large prospective ageing cohorts from the UK, the US, and continental Europe, providing a large sample, long follow-up, and substantial numbers of incident events. Repeated assessments allowed us to derive one-wave-lagged, time-updated cumulative average measures of sensory impairment. Exposure in the event interval was based solely on assessments made before that interval, and no person-time was included after the event. This design prevented sensory measurements obtained at or after outcome ascertainment from contributing to the exposure and strengthened the temporal ordering of exposure and outcome. We examined visual impairment, hearing impairment, and DSI alongside CMD and each of its components, allowing their associations with cardiometabolic health to be compared directly. Finally, findings were broadly consistent across restricted cubic spline analyses, random-effects meta-analyses, subgroup analyses, and the 2-year lag analysis.

Limitations

This study has several limitations. First, residual confounding and reverse causation cannot be excluded in an observational study [48]. Although we excluded participants with the relevant condition at baseline and in the first 2 years of follow-up, subclinical cardiometabolic abnormalities could have affected sensory function before diagnosis. Second, sensory impairment and CMD outcomes were based primarily on self-report and were therefore susceptible to measurement error and misclassification. Because outcomes were assessed at discrete survey waves, the date of first report might not correspond to disease onset or initial clinical diagnosis. Third, cumulative average scores assigned equal weight to each sensory assessment and did not account for unequal intervals between waves. They therefore represent average impairment across repeated assessments rather than time-weighted cumulative exposure. Finally, survey frequency, questionnaire wording, and health-care contexts differed across cohorts. Within-cohort analyses and random-effects meta-analysis reduced, but did not eliminate, concerns about cross-cohort comparability. Because participants were predominantly middle-aged and older adults from Europe and the US, the findings might not generalise to other populations.

Conclusion

Across three large ageing cohorts, higher time-updated cumulative average visual impairment, hearing impairment, and DSI were associated with greater risk of incident CMD. Associations were most consistent for DSI and extended to heart disease, diabetes, and stroke. Combined assessment of visual and hearing function might therefore complement conventional cardiometabolic risk assessment in middle-aged and older adults. Further research should determine whether sensory assessment improves risk prediction and whether interventions that preserve sensory function affect CMD risk.

Abbreviations

DSI: dual sensory impairment

CMD: cardiometabolic disease

Declarations

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Authors' contributions

SYC contributed to conceptualization, data curation, methodology, formal analysis, and writing—original draft preparation. WTH contributed to data curation, visualization, and validation. SXH contributed to writing—original draft preparation, visualization, and writing—review and editing. MHF contributed to project administration, conceptualization, supervision, and writing—review and editing. HZY contributed to project administration, conceptualization, supervision, and writing—review and editing.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Clinical trial number

Not applicable.

Availability of data and materials

The datasets supporting the conclusions of this article are available in the Gateway to Global Aging Data repository (<https://g2aging.org/>).

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Figures

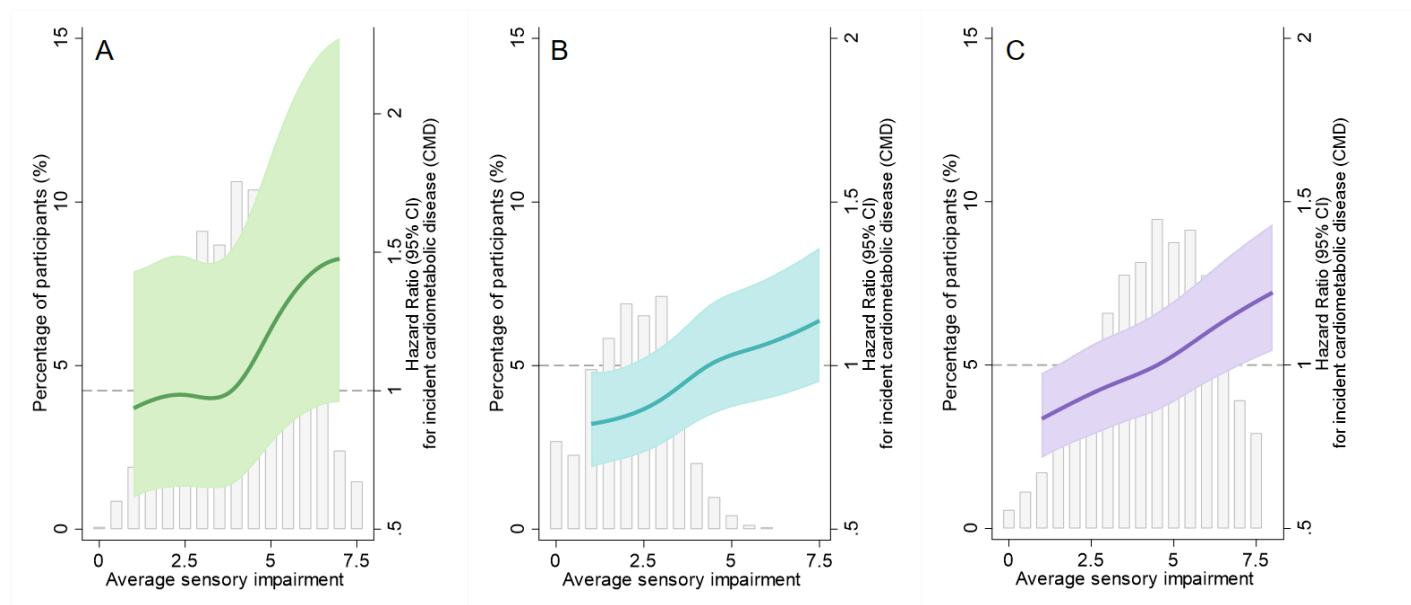


Figure 1

Dose-response association between time-updated cumulative average dual sensory impairment and incident cardiometabolic disease in ELSA, HRS, and SHARE

Extended Cox models with restricted cubic splines were fitted for cumulative average DSI and incident CMD. Panels A–C show ELSA, HRS, and SHARE, respectively. Solid lines and shaded areas indicate adjusted HRs and 95% CIs; dashed lines indicate an HR of 1. Histograms show the exposure distributions.

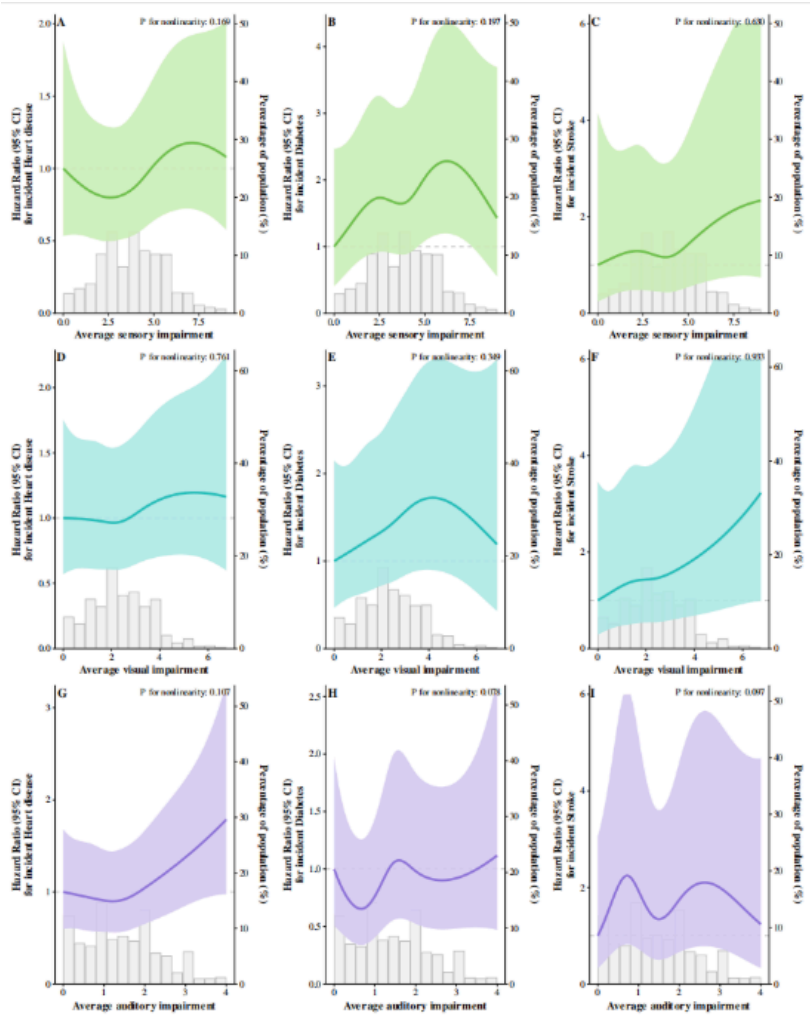


Figure 2

Dose–response associations of cumulative average sensory impairment with incident heart disease, diabetes, and stroke in ELSA

Extended Cox models with restricted cubic splines were fitted. Solid lines and shaded areas indicate adjusted HRs and 95% CIs; histograms show the exposure distributions.

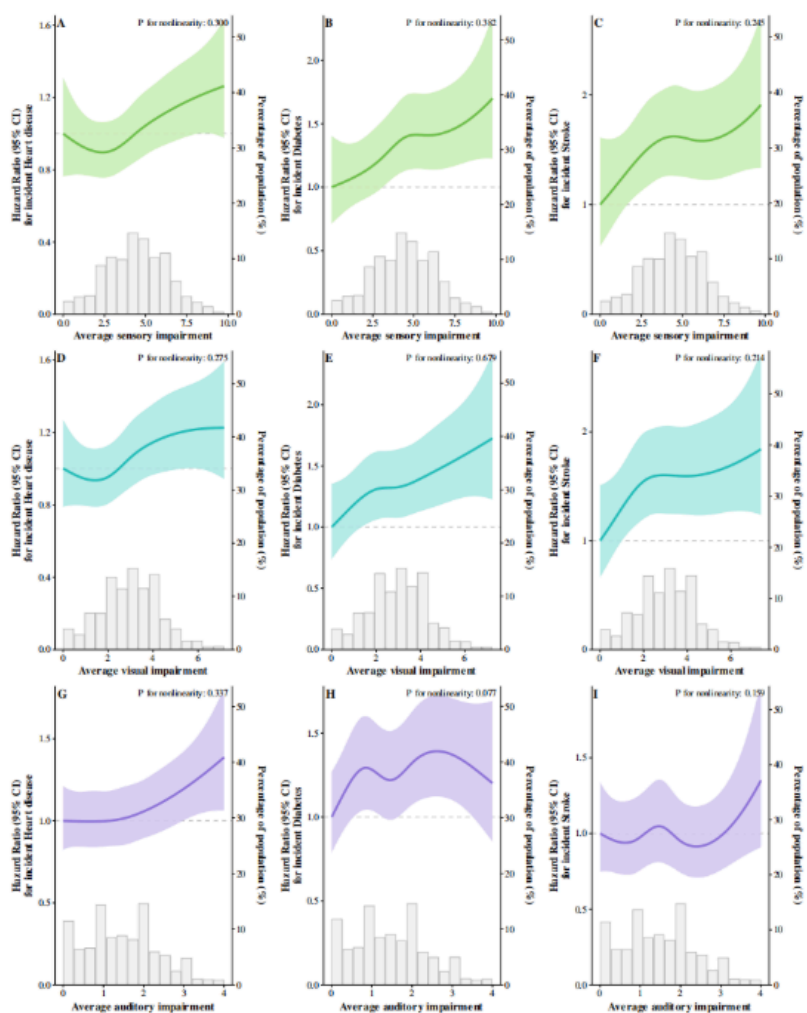


Figure 3

Dose–response associations of cumulative average sensory impairment with incident heart disease, diabetes, and stroke in HRS

Extended Cox models with restricted cubic splines were fitted. Solid lines and shaded areas indicate adjusted HRs and 95% CIs; histograms show the exposure distributions.

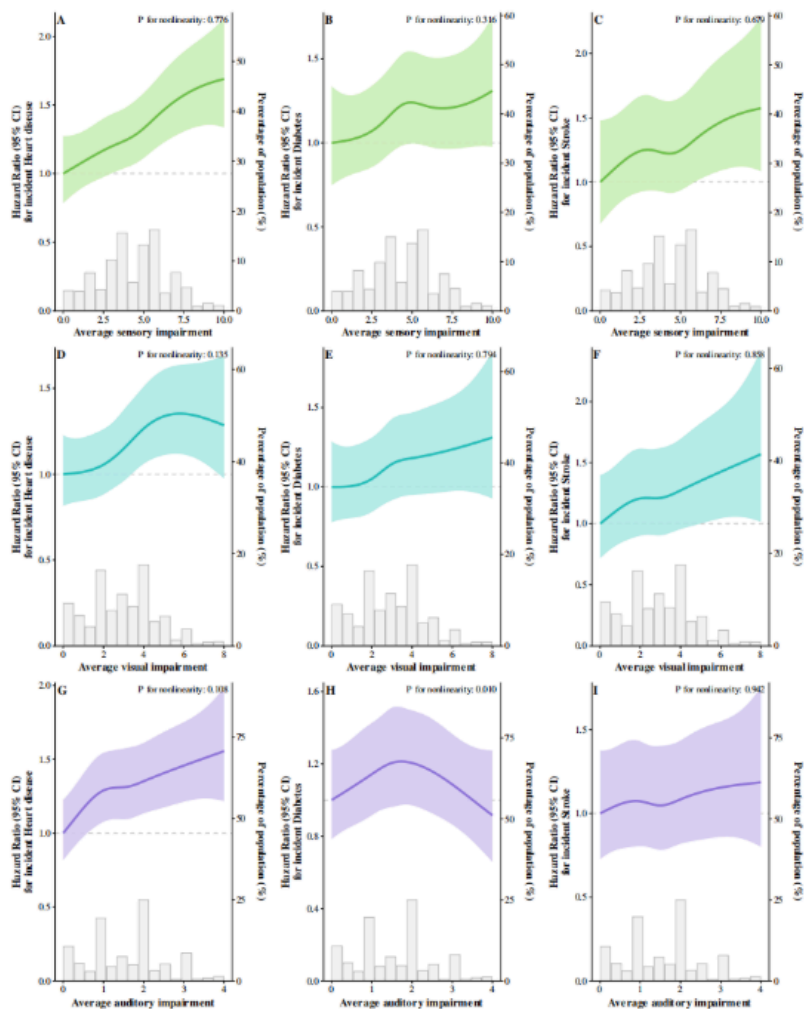


Figure 4

Dose–response associations of cumulative average sensory impairment with incident heart disease, diabetes, and stroke in SHARE

Extended Cox models with restricted cubic splines were fitted. Solid lines and shaded areas indicate adjusted HRs and 95% CIs; histograms show the exposure distributions.

Supplementary Files

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