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Elucidating The Burden of Dual-Sensory Impairment in Community-based Older Individuals in a Multi-Ethnic Society

Running Head: Burden of Three Forms of Dual-Sensory Impairment

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ABSTRACT

We aimed to determine the prevalence, risk factors, patient-centered impact and health-related costs of three types of dual sensory impairment (DSI) in a multi-ethnic older Asian population.

In this population-based, cross-sectional study (2017-2022) of 2,048 Asian adults aged ≥60 years, vision, hearing and olfactory impairments (VI, HI and OI) were assessed using validated clinical tests. DSI types included: VI+HI, VI+OI, and HI+OI. Age-, sex-, and ethnicity-adjusted prevalence rates (2020 Singapore Census) were calculated. Regression analyses identified associated risk factors, impacts and healthcare costs.

Of the 2,048 participants (mean age□standard deviation 75.7□7; 49.5% female), prevalence rates of VI+OI, VI+HI, OI+HI were 1.0%, 7.3% and 21.7%, respectively. Older age (odds ratio[OR]1.22) and multimorbidity (OR3.74) were significantly associated with VI+HI, while older age (OR1.23), males (OR3.62), living alone (OR2.37) and current smoking (OR2.51) were associated with higher odds of OI+HI. VI+HI was associated with lower HRQoL-scores (β:-0.026), while VI+HI (OR2.39) and OI+HI (OR2.10) were associated with lower IADL status. The OI+HI group showed a trend toward higher healthcare costs compared to those without.

DSI, particularly OI+HI, is relatively prevalent in older Singaporean adults. Early identification and targeted screening of at-risk groups may mitigate adverse outcomes and healthcare cost, given the global ageing population.

Key Words: DSI; Epidemiology; Risk factors; Determinants; Patient Centered Impact; Health Care costs

Word Count: 200

INTRODUCTION

Global projections estimate that by 2050, the proportion of people aged ≥60 years will nearly double, with the largest increase estimated to be in Eastern and Southeast Asia.[1] Ageing is associated with declines in sensory acuity,[2-4] and the proportion of individuals with any sensory impairment will also approximately double by 2050.[5,6] Dual sensory impairment (DSI, often defined as concurrent vision impairment [VI] and hearing impairment [HI]), is also highly prevalent in older adults[7,8] and has been shown to have more deleterious consequences than single sensory loss.[9,10] However, in recent years, there is growing interest in age-related olfactory impairment [OI], as it has been found to be a strong predictor of several adverse health outcomes, including cognitive impairment.[11,12] In this paper, we define DSI as any combination of two sensory impairments of either VI, HI or OI.

Large population-based studies on DSI (without OI in their definition) have shown prevalence rates ranging from 0.9% to 49.7%,[13] with determinants such as smoking and cardiovascular disease (CVD);[14] associated with health impact factors such as lower quality of life (QoL) scores;[15] and increased health care costs.[16] However, most were conducted in Western Europe or North America[7] with only a minority of studies conducted in Asian populations, meaning findings to date may not be generalized to the Asian population due to cultural, environmental, and life-style differences. In addition, many studies have assessed DSI via self-report,[17-24] or unvalidated questionnaires with 1-2 items,[7] which limit the accuracy of these results. Moreover, studies on the prevalence and determinants of DSI that included OI in their definition remain scarce despite the high prevalence of OI (~50%) among older adults and its substantial health-related burden, such as decreased QoL.[25] [26,27] Similarly, studies on the economic burden of DSI are lacking with only a handful of population-based studies

reporting on the association between increased healthcare spending and DSI (without OI in their definition), and the cost studies performed in Asia have used self-report rather than objectively assessed sensory impairment (i.e. VI, HI or OI).[16,28,29] These are important knowledge gaps given the increasing prevalence and adverse impact of DSI against the backdrop of a rapidly ageing global population.

In this paper, with the inclusion of OI as part of DSI definition, we report on the prevalence; risk determinants; associated patient-centred impact and economic burden of three DSI combinations (VI + HI; HI + OI or OI + VI) in a large, multi-ethnic community-dwelling population of Singaporean adults aged ≥60 years participating in the PopulatION Health and Eye Disease Profile in Elderly Singaporeans (**PIONEER)** study. We hypothesized considerable but differing prevalence estimates of DSI combinations; and that several sociodemographic (e.g., age and sex), lifestyle factors (e.g., smoking) and systemic conditions would be associated with these DSI combinations. We also expect worse patient centered and economic outcomes in participants with these combinations DSI as opposed to those with no sensory impairment (NSI). Elucidating the burden of various DSI combinations, and the impact of sociodemographic and lifestyle differences amidst disparities in health outcomes across ethnic lines, may help to inform more targeted public health strategies.

METHODS

Study Design and Population

PIONEER is a population-based study of 2643 community-dwelling Chinese, Malay, and Indian adults aged ≥60 years living in Singapore. The baseline visit was conducted between 2017 and 2022, and a detailed methodology has been published previously (**Supplementary Materials 1**).[30]

Of the 2643 participants, 595 were excluded for our analysis due to age (aged less than 60 years n=2), other races (n=5), or missing data on visual acuity (n=13), Sniffin' Sticks test (n=536), or hearing assessment (n=383; comprising assessments not performed [n = 118], unreliable results [n = 132], or incomplete testing in both ears [n = 133]), leaving in 2048 participants for this study (**Supplementary Figure S1**). The missing olfaction data reflect the initial study design, when the initial focus was primarily on vision and hearing. Olfactory assessment was only added to the PIONEER protocol ~9 months after study inception. For the prevalence estimates, all 2048 participants were included. However, for the determinant and impact analyses, an additional 995 participants were excluded due to having single sensory impairment (SSI; n=816) or multiple sensory impairment (MSI; n=179), resulting in 1053 participants for these specific analyses. SSI and MSI were excluded because this study focuses specifically on DSI, and MSI has been addressed in a prior publication.[31] To assess potential systematic differences or selection bias, key demographic and clinical characteristics were compared between participants with complete data who were included in the analysis and those with missing data who were excluded (**Supplementary Table S1**). The table shows that the two groups were largely comparable; included participants were younger than those excluded, while sex, socioeconomic status, overall comorbidity, and other characteristics were similar between groups.

All study procedures were approved by the SingHealth Centralized Institutional Review Board (CIRB, Reference #2016/3089) and adhere to the principles of the Declaration of Helsinki. Written consent was obtained from all participants.

Assessment and Definitions of Vision, Hearing, Olfactory Impairments

Presenting distance visual acuity (PDVA) was measured monocularly using a logMAR number chart (Lighthouse International, Distance VA Number Chart) at 4 m with participants wearing their habitual optical correction (if any), under standard photopic conditions (85 cd/m^2). If the participants were unable to read the largest line of letters, the chart was moved to 2 m. However, if they were still unable to read any letters at 2 m, finger counting, hand movements and the ability of the eye to perceive light with a pen torch were assessed. Presence of VI was defined as PDVA worse than 20/40 (> 0.3 logMAR) in the better eye in accordance with the World Health Organization (WHO) criteria for visual impairment.[32] We also utilized VI in the worse eye in supplementary analyses (**Supplementary Materials 2**).

Hearing for each ear was quantified by a trained study coordinator using a portable pure tone audiometer (SHOEBOX Audiometer - Clearwater Clinical Limited, Ottawa, Canada) in a quiet room with background noise monitoring. Air-conduction thresholds at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were recorded, and pure tone average (PTA) was calculated. HI was defined by PTA >25 dB in the better ear in accordance to the WHO criteria for HI.[33] We also conducted sensitivity analyses using HI definition in the worse ear in **Supplementary Materials 2**.

The 16-item identification segment of the Sniffin' Sticks test battery was used to determine olfactory function. Odour impregnated felt pen tips were presented at intervals of 30 seconds of each test-odor presentation, and participants were tasked to select the correct odorant descriptor from four multiple choice questions. The number of correct answers were summed in an overall score, with the maximum score being 16.[34] Any OI was defined as a score of <11 based on updated cut-points published by Hummel and colleagues.[35,36]

Any DSI was defined as any impairment of two senses as described above i.e., HI + VI, HI + OI, or VI + OI. NSI was defined as the absence of VI, HI and OI.

Assessment of Health-related Outcomes

Trained research staff conducted face-to-face interviews to collect the following questionnaire data and performed standardized clinical examinations for the clinical data. *Health-Related Quality of Life (HR-QoL)* was assessed using the EuroQoL5-Dimensions Health States (EQ-5D-5L),[37] which evaluates 5 different health states: mobility, self-care, usual activity pain/discomfort and anxiety/depression. A utility index ranging from 1 (perfect health) to -0.59 (worse health) was calculated for all participants using established UK EQ-5D tariffs.[38] The UK value set was used for comparability with regional studies, as the Singaporean EQ-5D-5L set was unavailable when PIONEER began.[39] *Life-space mobility* was quantified using the Life-Space Questionnaire,[40] which was adapted for use in a Singaporean context. The 7-item questionnaire is designed to determine the life-space accessed (e.g., house, neighborhood, country) within the past 3 days of the participant. Each item is scored 1 with 'yes', and 0 with 'no'. The maximum score is 7, corresponding with the largest life space mobility possible. Low life-space mobility was defined as a score of <5 (median). Presence of low *Instrumental Activities of Daily Living* (IADL) was determined using the 8-item Lawton IADL scale.[41] Items were recoded to reflect increasing independence of the individual, with a score of 0 being the least independent and 2 being the most independent. 'Dependent, low function' is defined as a total Lawton score of <16. *Falls and fall frequency* over the past 12 months were quantified using an in-house questionnaire; and *hospitalization frequency and duration* over the past 6 months were assessed using the modified healthcare services expenditure

module.[42] This module was also used to assess *direct healthcare expenditure*, comprising hospitalization and emergency department visit costs over the past 6 months, and mental health and outpatient service utilization over the past 3 months, extrapolated to annual healthcare expenditure.

Dual Energy X-Ray Absorptiometry (DXA; Discovery-W. Hologic Inc. Bedford-MA) was used to measure whole and regional body compositions, including fat and muscle mass, and bone mineral density (BMD). Based on the Asian Working Group for Sarcopenia (2019) recommended cut-offs, sarcopenia was defined as having low appendicular muscle mass (men <7 kg/m^2, women <5.4 kg/m^2) in the presence of either low grip strength (men <28 kg, women <18 kg) or low gait speed (<1m/s).[43] *BMD* was classified according to the WHO criteria for this age group, based on DXA measured T-scores of the lumbar spine, and/or femoral neck, and/or total hip as follows: normal (T-score > -1 SD), osteopenia (-1 ≥ T-score > -2.5 SD), and osteoporosis (T-score ≤ -2.5SD).[44] Therefore, osteoporosis was defined a low BMD (T-score, ≤ −2.5) in any of the following sites: hip, femoral, neck, and lumbar spine. *Frailty* was defined according to the modified Fried criteria[45] as having 3 or more of the following conditions: shrinkage (Body Mass Index [BMI] <18.5), low gait speed (<1.0m/s assessed using a 4 m gait speed test), low grip strength (men <28 kg, women <18 kg quantified using a digital hand dynamometer (JAMAR Plus+, JLW instruments, Illinois, USA)), exhaustion (score of <10 for three questions from the vitality domain of the 12-item Short-form survey SF-12), low physical activity levels (defined as the sex-specific lowest quintile of total self-reported duration spent carrying out moderate and vigorous activity (e.g., gardening, brisk walking, dancing, jogging).[45]

Assessment of Covariates

Participants' sociodemographic details, including age, sex, ethnicity, socioeconomic status (SES); self-reported medical history (presence of diabetes, hypertension, dyslipidemia, cardiovascular disease, chronic kidney disease; number of medications); and lifestyle factors (smoking status and frequency of alcohol consumption) were collected via an in-house questionnaire. *Low SES* was defined as having primary or lower education and a monthly household income below $2000 SGD.[46] Clinical covariates were collected via standardized clinical examination: weight and height were measured using a wall-mounted, adjustable measuring scale and a calibrated scientific weight scale, respectively. *BMI* was calculated as weight in kilograms divided by height in meters squared (Weight[47]/Height[m]^2). BMI was categorized as underweight (<18.5), normal (18.5≤BMI<23), overweight (BMI ≥23 to 27.5), and obese (BMI>27.5) according to Asian cut-offs.[48] Systolic and diastolic blood pressure was measured twice using an automated blood pressure (Dinamap Pro Series DP110X-RW; GE Medical Systems Information Technologies, Inc), with a third reading taken if the two previous systolic or diastolic readings differed by more than 10- or 5-mm Hg, respectively. The mean of the closest two readings was used in analyses. *Hypertension* was defined as SBP ≥ 140mmHg, DBP ≥ 90mmHg, self-reported use of anti-hypertensive medications, or self-reported history of physician-diagnosed hypertension.[46] Blood samples were collected for hemoglobin A1c (HbA1c); random glucose; total, high-density lipoprotein and low-density lipoprotein cholesterol; and triglyceride levels. *Diabetes* was defined as random glucose ≥ 11.1mmol/L, HbA1c ≥ 6.5%, self-reported use of diabetic medication or reported history of physician-diagnosed diabetes.[46] *Dyslipidemia* was defined as total cholesterol ≥ 5.2 mmol/L, LDL cholesterol ≥ 3.4 mmol/L, triglycerides ≥ 1.7 mmol/L or use of anti-cholesterol medication.[46] *Polypharmacy* was considered present if the patient was taking 5 or more medications (excluding short-term

medication, e.g., pain; supplements; or vitamins). *Chronic kidney disease* (CKD) was defined as an estimated glomerular filtration rate (eGFR) <60mL/min/1.73m^2 [49] and *CVD* was defined as having a history of angina, stroke, or heart attack. Lastly, *multimorbidity* was defined as having ≥ 3 of the following systemic conditions: diabetes, hypertension, dyslipidemia, CVD, CKD.

Statistical Analyses

Descriptive statistics were performed to characterize the study population. Continuous variables were described with means and SDs. Categorical variables were reported using numbers and percentages. As we oversampled minority races, females, and older participants, the overall, age-, sex-, and ethnicity-stratified prevalence rates for DSI combinations were determined by weighting individuals according to their sampling probabilities and standardizing to Singapore's 2020 population census.

To identify the determinants of the three types of DSI, we performed logistic regression analysis, including pre-defined determinants such as age, sex, ethnicity, low SES, living alone, BMI category, smoking status, alcohol consumption frequency, polypharmacy and multimorbidity into the model, followed by a dominance analysis to assess the individual contribution of each determinant to the overall model. To improve interpretability and model parsimony, backward elimination using the Akaike Information Criterion (AIC) was applied to derive reduced models. The outcome of interest was participants with a particular type of DSI (e.g., VI+HI), with the reference group being those with NSI.

To determine the associations between DSI and patient-centered outcomes, we performed multivariable linear regression analysis on continuous outcomes (i.e., Health-Related Quality of Life (EQ-5D-5L) and life-space mobility) and

multivariable logistic regression analysis on binary outcomes (i.e., low IADL status, falls, hospitalizations, osteoporosis, frailty and sarcopenia). The reference group for the multivariable regression was NSI. We utilized two-part models to determine the associations between DSI and health care costs. The first model consists of logistic regression models, and the second model consists of gamma generalized linear models with log link function. All analyses were adjusted for potential confounders, such as age, sex, ethnicity, low SES, living alone, smoking status, polypharmacy and multimorbidity.

All statistical analyses were performed using R version 4.3.1. A p-value (2-sided) <0.05 was considered statistically significant. Additional sensitivity analyses using worse eye/ear definitions for DSI were performed and provided in **Supplementary Materials 2.**

RESULTS

The any DSI group (n=711 after applying all predefined inclusion and exclusion criteria) was on average 75.7 ±7.8 years old, of which 352 (49.5%) were female, and 348 (48.9%), 195 (27.4%), 168 (23.6%) were Chinese, Malays and Indians, respectively. A descriptive summary of the demographic, systemic, socioeconomic characteristics and health-related outcomes stratified by DSI status is provided in **Table 1**.

The crude prevalence of VI + OI, VI+HI, OI + HI was 0.7%, 8.4% and 25.5%, respectively; and the related census-adjusted prevalence was 1.0%, 7.3% and 21.7%, respectively (**Tables 2**). Overall, the weighted prevalence of DSI combinations (except VI+OI) increased with age (p-trend <0.05, **Tables 2**). Sex-stratified results revealed no difference in the prevalence between males and females in VI+OI group, while females had higher prevalence rates of VI+HI than males, both overall (9.4% in females vs 5% in males) and across age groups, and

males had higher prevalence rates of OI+HI than females, both overall (28.8% in males vs 15.3% in females) and across age groups (**Figure 1A**). Ethnicity stratified analyses showed no difference in the prevalence of DSI combinations across the three ethnic groups sampled (**Figure 1**B).

As stated above, only 1053 participants (711 with any DSI and 342 with NSI) were included in the determinants, impact and costs analyses. Moreover, because of the low number of individuals with VI+OI, this DSI combination was not included in risk determinant, impact and cost analyses. In adjusted models (**Tables 3**) older age was significantly associated with VI + HI: OR 1.22 [95%CI: 1.16, 1.29] and OI + HI: OR 1.23 [95%CI: 1.19, 1.28]. Dominance analysis showed that age contributed 70.4% and 70.8% of the variance for VI +HI and OI + HI, respectively. Multimorbidity was associated with increased odds of VI + HI (OR 3.74 [95%CI 1.86, 7.69]), and contributed 10.8% of the variance, while obesity was associated with decreased odds of VI + HI (OR 0.19 [95%CI: 0.19, 0.77]) and contributed 2.5% of the variance. In the reduced model, current smoking was borderline associated with increased odds of VI + HI (OR 2.83 [95%CI 0.94, 8.21]; **Supplementary Table S2A**).

Male sex (OR 3.62 [95% CI: 2.26, 5.88]), current smoking (OR 2.51 [95% CI: 1.21, 5.40]), and living alone (OR 2.37 [95%CI 1.09, 5.40]) were associated with increased odds of OI + HI and contributed 13.9%, 2.9% and 2.7% of the variance, respectively. The risk determinants remained consistent in the reduced model (**Supplementary Table S2B**).

In multivariable regression models, VI + HI was significantly associated with lower HRQoL scores (B: -0.026 [95%CI -0.050, -0.001]). VI + HI and OI + HI were significantly associated with lower IADL status, (OR: 2.39 [95% CI 1.17, 4.91]) and (OR: 2.10 [95% CI 1.15, 3.91]), respectively. We found no significant associations between DSI combinations and life space mobility, falls,

hospitalizations, osteoporosis, frailty, and sarcopenia (**Table 4**). Similar findings were observed in sensitivity analyses when all three DSI combinations, including VI + OI, were analyzed (**Supplementary Table S3**).

Compared to individuals with NSI, the OI+HI group showed a trend toward higher healthcare costs, although the estimates lacked precision (2.04; 95% CI: 0.79–5.31; **Table 5**). This pattern remained consistent in sensitivity analyses that additionally included VI + OI (**Supplementary Table S4**).Using worst eye/worst ear definitions (**Supplementary Materials 2)**, census-adjusted prevalence rates were slightly higher as expected: census-adjusted prevalence of VI + OI, VI + HI, and OI + HI was 2.0%, 22.0% and 15.0%, respectively. Further analyses of risk factors showed older age and smoking were associated with VI+HI, while age, male sex and smoking were associated with OI+HI. Surprisingly, except for VI+OI that was associated with lower odds of osteoporosis (OR 0.112 [CI: 0.006, 0.600]), no significant associations between DSI categories and any other patient centred outcomes were observed.

DISCUSSION

In our nationally representative sample of older Singaporean adults, we found for the first time that of the three DSI combinations, OI + HI was most prevalent, in over one in five participants. Several sociodemographic (older age, male sex, living alone), lifestyle (smoking), and health-related factors (multimorbidity) were associated with the DSI combinations assessed, with older age being the major driving factor overall. Several DSI combinations were associated with lower HR-QoL scores and low IADL status. Only those with OI+HI showed a trend toward higher healthcare cost than those without. Our findings demonstrate the importance of screening for DSI combinations, particularly OI+HI, in older male adults and those who smoke and live alone for early

detection and timely management via relevant intervention strategies such as hearing aids, ophthalmic aids or possible olfactory training. Longitudinal studies are needed to determine the predictors of incident DSI combinations and gain a deeper understanding of underlying mechanisms.

As our study is the first population-based study to report on the prevalence of “OI+” DSI combinations, it is difficult to compare results pertaining to such combinations to existing literature. However, the VI+HI prevalence rate of 7.3% is comparable to previously reported VI+HI prevalence rates in Singaporean studies. For example, Phua and colleagues reported a self-reported DSI prevalence rate of 12.8%[50] in a large population-based study of 4077 participants, while Tareque and associates found a prevalence rate of 11.6%[51] in their large population-based study of 3452 subjects (self-reported VI and HI). Elsewhere in Asia, a small Malaysian study of 229 community-dwelling subjects reported a prevalence rate of 8.3%[52] for VI+HI (objectively assessed HI and VI), while two larger population-based studies of older adults in Malaysia (objectively assessed HI and VI)[53] and Japan[19] (self-reported VI and HI) reported prevalence rates of 10.5% and 11.4%, respectively. These slight inconsistencies may be explained by different methods of sensory assessment (e.g., self-report vs objective measurement) and varying definitions of VI and HI (self-reported vs objectively assessed), different characteristics of participants (e.g., older age, more comorbidities), and different access to health care facilities across countries (e.g., rural vs. urban areas). Our finding that OI+HI was the most prevalent combination of DSI compared to VI+HI or VI+OI in Asian older adults, could be attributed to OI and HI being closely related senses. Studies have demonstrated that conductive smell and hearing disorders are often comorbid, such as chronic rhinosinusitis and otitis media.[54] Furthermore, both these senses are often the most vulnerable to a wide range of chemcial and auditory environmental

pollutants/damage, and have limited capacity for regeneration, particularly among older adults.[55] The fact that OI+HI is the most prevalent DSI combination in our study participants highlights the need for community-based initiatives to screen for OI-related DSI in at-risk older adult populations.

It is noteworthy that <1% of our population were using hearing aids. While vision may be considered more vital to patients, and thus patients are more likely to either undergo corrective surgery or wear glasses to help them correct their VI, this may be less so for HI, and even less so for OI. There may also be less surgically correctable diseases for HI and OI compared with VI, meaning that prevention may be more important than cure.

Similar to previous studies[56-58] that have reported older age as a risk factor of DSI, the present study confirmed age as a major determinant of three combination DSI. The presence of DSI in older individuals is likely due to age-related anatomical and physiological changes of the sensory systems.[59] VI among older adults can, for example, can be explained by pupillary miosis; and increased rates of cataract[4] and age-related macular degeneration;[60] HI may be due to degeneration of the neural elements, metabolic changes, and stiffening of membranes in the inner ear,[61] and OI caused by head trauma, exposure to environmental pollutants and chemicals, and age related reductions in the number of olfactory receptor cells, cell regeneration and structural and functional changes in the olfactory system.[62,63] Other studies have also reported the association of DSI and male sex.[23,64] We found that male sex was significantly associated with over a 3 to 4-fold increased odds of OI+HI, similar to a finding where male sex was reported as a risk factor for HI[65] and OI.[66] This may be because men are more likely to work in environments with harmful noise exposure often associated with hearing loss.[67] Moreover, men may have higher exposure to industrial chemicals (including cadmium, chromium, nickel, acrylate, styrene,

toluene, formaldehyde, etc.) which are known to be both olfactotoxic and ototoxic.[68,69] Living alone has also been identified by previous studies as a risk factor for DSI,[70] corroborating our findings of an increased likelihood of OI+HI in those living alone. Importantly, being a current smoker was significantly associated with almost a threefold increased odds of OI+HI, with similar results being shown in previous studies.[71] These findings highlight the need for targeted messaging about the negative impact of smoking on sensory health.

Next, multimorbidity showed an almost 4-fold increased odds for VI + HI, suggesting the need for further investigation on potential underpinning mechanisms. Various neuropathic and angiopathic manifestations consequent to diabetes, dyslipidemia, hypertension, CKD, and CVD might be a related plausible explanation.[72,73] For example, individuals with diabetes or CVD may develop microangiopathic changes in the retina and cochlea which may decrease microcirculation to these areas, potentially resulting in sensory impairment. Surprisingly, overweight/obesity was unexpectedly associated with lower odds of VI+HI; possibly reflecting the obesity paradox.[74] While DXA-measured fat mass was available in PIONEER, BMI was used here for consistency with prior studies and because it remains a pragmatic population-level measure; however, it may not fully capture body composition in older adults. This finding should be interpreted cautiously, as reverse causation, residual confounding, or survivorship bias may contribute, and should be viewed as hypothesis-generating rather than protective. However, it’s worth considering if these are simply associations, in which case DSI is a marker of a more general decline but not causally implicated in changes that otherwise lead to the conditions listed - **OR** - are there plausible causal pathways, such as OI could be related to a shift in food preferences or appetite that can lead to dietary changes that could support the development of chronic nutrition diseases such as diabetes.

Like other studies,[70,75] we found an association between VI+HI and a decreased HR-QoL scores. However, other DSI combinations did not show these associations, and this might be because the EQ-5D-5L is a generic HR-QoL questionnaire and may be insensitive at measuring the impact of specific sensory impairments. Hence, other sensory-impairment specific QoL instruments might be more useful in DSI future research.[76,77] Moreover, we found that VI+HI and OI + HI was associated with increased odds of low IADL status, like the population-based study of 4214 older adults in Japan by Tomida and associates.[78] This finding is not unexpected given that performing daily activities can be more difficult in the presence of sensory losses.

Unlike other studies,[79-81] we found no significant relationship between all DSI combinations and falls and hospitalization. This may be due to the concept of 'silent-fallers', as many elderly do not report their falls or may not be able to recall them, resulting in a recall bias in our study.[82] This is complicated by the fact that we were unable to access participant's medical history and history of falls to verifying participant self-report due to Singapore's strict data protection laws. Additionally, none of the DSI combination was associated with frailty and sarcopenia in our study, a finding which aligns with some studies and not others.[20,83] Future research is warranted in this area.

A trend toward higher health care costs was observed in the OI+HI group, consistent with prior studies by Ding and colleagues,[16] and Deardorff and colleagues,[28] which reported higher healthcare utilization and costs among individuals with DSI (VI+HI).

To our knowledge, this is the first Asian study to evaluate the economic implications of objectively assessed dual sensory impairment combinations. While our results indicate a trend toward higher healthcare costs among individuals

with DSI, further studies are needed to confirm these associations and to better understand their policy and healthcare system implications.

Strengths of this study include a well-characterized, representative sample of older Singaporeans, the objective assessment of sensory impairments and the inclusion of OI which is rarely included in most DSI studies despite its high burden. We supply additional analysis using the worse eye and ear which allowed us to capture those with unilateral as well as bilateral disease, creating a more accurate picture of the continuum of sensory impairments and thus making our study more inclusive. It also creates the future opportunity to investigate whether those with unilateral DSI vs bilateral DSI might benefit from earlier interventions to either prevent or mitigate their sensory impairments as early as possible.

However, several limitations should also be noted. Audiometry was performed using pure tones between 500 and 4000hz, to calculate a pure tone average. Higher frequencies were not tested, thus participants with only high frequency hearing loss were not accounted for in this study. Also, other sensory impairments such as taste and tactile dysfunction were not investigated, which may also have impacted on our health-related outcome analyses. Next, due to the low numbers of the VI+OI group (n=15), potential risk factors could unfortunately not be presented, and future research with more VI+OI subjects is warranted. Some of the null associations observed in our study may reflect limitations in measurement sensitivity rather than a true absence of relationship. Lastly, any causal effects are unknown due to the cross-sectional design of our study. Longitudinal studies are needed to clarify directionality of the associated factors discovered in this study. To elucidate this, a 4.5-year follow-up visit for the PIONEER study (PIONEER II) has started, which will help to understand the changing prevalence of DSI better, determine the directionality of potential risk factors and gain a better understanding of the impact of DSI.

In conclusion, our study found for the first time that OI+HI was the most common type of DSI in Asian older adults, which was associated with a series of chronic diseases and also tended to incur a higher healthcare cost than those without. Older age exerted the largest influence across all types of DSI. Several DSI types were associated with lower HR-QoL scores and low IADL status. Screening for DSI, particularly OI+HI is warranted for early detection and timely management in this growing group of elderly. Future longitudinal research is needed to further explore the relationships between DSI combinations, its risk factors, and associated dietary and behavioral adaptations and patient-centered and economic burdens.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. All requests will be considered in accordance with institutional and ethical guidelines.

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ADDITIONAL INFORMATION

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Table 1. Demographic, systemic, and socioeconomic characteristics of participants in the PIONEER study, stratified by DSI status (NSI, DSI)

Characteristics	NSI (n=342)	DSI[1] (n=711)	Overall (N=1053)
	Mean (SD) or n (%)		
Age (year)	66.7 (5.4)	75.7 (7.8)	72.7 (8.3)
Female sex	238 (69.6)	352 (49.5)	590 (56.0)
Race			
Chinese	163 (47.7)	348 (48.9)	511 (48.5)
Malay	91 (26.6)	195 (27.4)	286 (27.2)
Indian	88 (25.7)	168 (23.6)	256 (24.3)
Low socioeconomic status	33 (9.6)	129 (18.1)	162 (15.4)
Living alone	18 (5.3)	87 (12.2)	105 (10.0)
BMI categories			
Underweight	15 (4.4)	32 (4.5)	47 (4.5)
Normal	89 (26.0)	198 (27.8)	287 (27.3)
Overweight/Obese	238 (69.6)	479 (67.4)	717 (68.1)
Smoking status			
Never smoked or past smoker	319 (93.3)	615 (86.5)	934 (88.7)
Current smoker	18 (5.3)	70 (9.8)	88 (8.4)
Alcohol frequency			
None	282 (82.5)	591 (83.1)	873 (82.9)
≤ 4 days/week	24 (7.0)	54 (7.6)	78 (7.4)
> 4 days/week	5 (1.5)	20 (2.8)	25 (2.4)
Polypharmacy	52 (15.2)	171 (24.1)	223 (21.2)
Any systemic condition	327 (95.6)	698 (98.2)	1025 (97.3)
Systemic conditions			
Diabetes	87 (25.4)	272 (38.3)	359 (34.1)
Hypertension	271 (79.2)	620 (87.2)	891 (84.6)
Dyslipidaemia	290 (84.8)	564 (79.3)	854 (81.1)
CVD	42 (12.3)	138 (19.4)	180 (17.1)
CKD	26 (7.6)	153 (21.5)	179 (17.0)
Multimorbidity	104 (30.4)	317 (44.6)	421 (40.0)

1. DSI subjects consists of 15 (2.1%) VI+OI subjects, 173 (24.3%) VI+HI subjects, and 523 (73.6%) OI+HI subjects.
BMI: Body Mass Index; CKD: Chronic Kidney Disease; CVD: Cardiovascular Disease; DSI: Dual Sensory Impairment; HI: Hearing Impairment; NSI: No Sensory Impairment; OI: Olfactory Impairment; SD: Standard Deviation; VI: Visual Impairment.

Table 2. Weighted prevalence of DSI, stratified by age, sex and ethnicity in the PIONEER study.

Age group	All (N = 2048)		Sex				Ethnicity					
			Male (N = 919)		Female (N = 1129)		Chinese (N = 992)		Malay (N = 582)		Indian (N = 474)	
	n	Weighted, % (95% CI)	n	Weighted, % (95% CI)	n	Weighted, % (95% CI)	n	Weighted, % (95% CI)	n	Weighted, % (95% CI)	n	Weighted, % (95% CI)
VI+OI												
60-69	5	1.0 (0.3, 2.3)	4	1.5 (0.3, 4.0)	1	0.4 (0.0, 2.5)	4	1.1 (0.3, 2.8)	1	0.4 (0.0, 2.4)	0	-
70-79	6	0.9 (0.3, 2.2)	0	-	6	1.7 (0.5, 4.1)	4	1.0 (0.3, 2.5)	0	-	2	1.3 (0.2, 4.5)
≥ 80	4	1.1 (0.3, 2.9)	2	1.5 (0.2, 5.6)	2	0.9 (0.1, 3.2)	4	1.3 (0.3, 3.4)	0	-	0	-
P-trend		-		-		-		-		-		-
Total	15	1.0 (0.5, 1.8)	6	1.1 (0.3, 2.5)	9	0.9 (0.3, 1.9)	12	1.1 (0.5, 2.0)	1	0.3 (0.0, 1.6)	2	0.3 (0.0, 1.2)
VI+HI												
60-69	43	4.7 (3.1, 6.9)	15	3.6 (1.7, 6.6)	28	5.8 (3.3, 9.3)	16	4.5 (2.6, 7.2)	17	6.3 (3.7, 9.9)	10	5.1 (2.5, 9.2)
70-79	65	9.3 (6.9, 12.2)	17	5.9 (3.0, 10.2)	48	12.2 (8.7, 16.6)	35	9.3 (6.5, 12.7)	18	10.3 (6.3, 15.7)	12	7.9 (4.1, 13.5)
≥ 80	65	13.9 (10.0, 18.6)	23	9.7 (5.5, 15.6)	42	16.5 (10.8, 23.5)	34	14.3 (9.8, 19.7)	13	9.6 (4.9, 16.5)	18	13.9 (8.3, 21.3)
P-trend	P-trend <0.001		P-trend = 0.011		P-trend <0.001		P-trend <0.001		P-trend = 0.135		P-trend = 0.006	
Total	173	7.3 (6.0, 8.8)	55	5.0 (3.4, 7.0)	118	9.4 (7.4, 11.8)	85	7.3 (5.8, 9.1)	48	7.6 (5.5, 10.2)	40	6.9 (4.7, 9.7)
OI+HI												
60-69	123	14.9 (12.1, 18.2)	86	23.7 (18.6, 29.4)	37	6.4 (3.9, 9.9)	53	14.7 (11.3, 18.7)	39	15.6 (11.4, 20.7)	31	16.6 (11.6, 22.7)
70-79	198	27.3 (23.4, 31.5)	109	35.1 (28.5, 42.2)	89	20.6 (16.1, 25.7)	94	26.6 (22.2, 31.5)	57	31.4 (24.7, 38.8)	47	31.6 (24.3, 39.6)
≥ 80	202	37.5 (32.1, 43.3)	103	40.1 (32.4, 48.1)	99	35.9 (28.5, 44.0)	104	37.5 (31.3, 44.1)	50	37.5 (28.7, 47.0)	48	38.0 (29.6, 46.9)
P-trend	P-trend <0.001		P-trend <0.001		P-trend <0.001		P-trend <0.001		P-trend <0.001		P-trend <0.001	
Total	523	21.7 (19.5, 24.0)	298	28.8 (25.1, 32.8)	225	15.3 (13.0, 17.9)	251	21.6 (19.0, 24.3)	146	21.8 (18.4, 25.5)	126	23.1 (19.2, 27.3)

Weighted prevalences are calculated with sampling weights specific to each age group, sex and ethnicity to adjust for oversampling and post-stratification weights to align to the population distribution based on the 2020 Singapore Census. P-trend will not be

computed for counts less than 5 in any age group or if the total count is less than 20.
CI: Confidence Interval; DSI: Dual Sensory Impairment; HI: Hearing Impairment; OI: Olfactory Impairment; VI: Visual Impairment.

Table 3A. Factors associated with DSI (VI+HI)

Risk factor	Model		Dominance analysis	
	OR (95% CI)	P-value	Contribution [1] (%)	Rank [2]
Age (year)	1.22 (1.16, 1.29)	<0.001	70.4	1
Sex			0.1	9
Female	Reference	NA		
Male	0.89 (0.44, 1.77)	0.742		
Race			0.7	7
Chinese	Reference	NA		
Malay	1.20 (0.57, 2.54)	0.628		
Indian	0.89 (0.41, 1.88)	0.752		
Low socioeconomic status			13.4	2
No	Reference	NA		
Yes	1.73 (0.75, 3.95)	0.195		
Living alone			2.0	5
No	Reference	NA		
Yes	1.84 (0.62, 5.24)	0.260		
BMI categories			2.5	4
Normal	Reference	NA		
Underweight	0.88 (0.18, 3.38)	0.866		
Overweight/Obese	0.38 (0.19, 0.77)	0.007		
Smoking status			0.8	6
Never or past smoker	Reference	NA		
Current smoker	2.81 (0.85, 9.08)	0.085		
Alcohol frequency			-1.4	10
None	Reference	NA		
≤ 4 days/week	1.13 (0.37, 3.14)	0.814		
> 4 days/week	1.44 (0.17, 9.64)	0.711		
Polypharmacy			0.6	8
No	Reference	NA		
Yes	0.48 (0.20, 1.08)	0.081		
Multimorbidity			10.8	3
No	Reference	NA		
Yes	3.74 (1.86, 7.69)	<0.001		

1: Contribution is the standardized dominance statistics in the dominance analysis from the model.
2. The ranks of each predictor are ranked from predictors with the greatest contribution to the least.
Low Socioeconomic Status: Having primary or lower education and individual monthly income < SGD2000; BMI categories: BMI < 18.5 kg/m^2 as underweight, BMI between 18.5 and 22.9 kg/m^2 (inclusive) as normal, BMI ≥ 23 kg/m^2 as overweight/obese; Polypharmacy: Taking ≥ 5 medications (exclude supplements or vitamins); Multimorbidity: Having more than or equal to 3 systemic conditions (diabetes, hypertension, dyslipidemia, CVD, CKD).
BMI: Body Mass Index; CI: Confidence Interval; CKD: Chronic Kidney Disease; CVD: Cardiovascular Disease; DSI: Dual Sensory Impairment; HI: Hearing Impairment; OR: Odds Ratio; VI: Visual Impairment.

Table 3B. Factors associated with DSI (OI+HI)

Risk factor	Model		Dominance analysis	
	OR (95% CI)	P-value	Contribution [1] (%)	Rank [2]
Age (year)	1.23 (1.19, 1.28)	<0.001	70.8	1
Sex			13.9	2
Female	Reference	NA		
Male	3.62 (2.26, 5.88)	<0.001		
Race			0.3	10
Chinese	Reference	NA		
Malay	1.10 (0.64, 1.87)	0.730		
Indian	0.94 (0.54, 1.63)	0.823		
Low socioeconomic status			3.4	3
No	Reference	NA		
Yes	1.09 (0.57, 2.10)	0.791		
Living alone			2.7	6
No	Reference	NA		
Yes	2.37 (1.09, 5.40)	0.033		
BMI categories			0.3	9
Normal	Reference	NA		
Underweight	0.62 (0.19, 1.94)	0.423		
Overweight/Obese	1.13 (0.66, 1.92)	0.663		
Smoking status			2.9	5
Never or past smoker	Reference	NA		
Current smoker	2.51 (1.21, 5.40)	0.015		
Alcohol frequency			1.4	7
None	Reference	NA		
≤ 4 days/week	0.93 (0.45, 1.93)	0.842		
> 4 days/week	1.64 (0.46, 6.94)	0.469		
Polypharmacy			1.1	8
No	Reference	NA		
Yes	0.84 (0.45, 1.55)	0.578		
Multimorbidity			3.3	4
No	Reference	NA		
Yes	1.11 (0.65, 1.88)	0.701		

1: Contribution is the standardized dominance statistics in the dominance analysis from the model.
2. The ranks of each predictor are ranked from predictors with the greatest contribution to the least.
Low Socioeconomic Status: Having primary or lower education and individual monthly income < SGD2000; BMI categories: BMI < 18.5 kg/m^2 as underweight, BMI between 18.5 and 22.9 kg/m^2 (inclusive) as normal, BMI ≥ 23 kg/m^2 as overweight/obese; Polypharmacy: Taking ≥ 5 medications (exclude supplements or vitamins); Multimorbidity: Having more than or equal to 3 systemic conditions (diabetes, hypertension, dyslipidemia, CVD, CKD)
BMI: Body Mass Index; CI: Confidence Interval; CKD: Chronic Kidney Disease; CVD: Cardiovascular Disease; DSI: Dual Sensory Impairment; HI: Hearing Impairment; OI: Olfactory Impairment; OR: Odds Ratio.

Table 4. Associations between DSI and patient-reported outcomes

PRO	Exposure	Estimate[1] (95% CI)	P-value	Overall marginal effect (95% CI)	Change (%)
EQ-5D-5L					
	NSI	Reference	NA	NA	NA
	VI+HI	-0.026 (-0.050, -0.001)	0.040	-0.026 (-0.050, -0.001)	-2.81
	OI+HI	0.004 (-0.015, 0.023)	0.690	0.004 (-0.015, 0.023)	0.42
Life space mobility					
	NSI	Reference	NA	NA	NA
	VI+HI	-0.152 (-0.346, 0.043)	0.127	-0.152 (-0.346, 0.043)	-3.30
	OI+HI	-0.114 (-0.264, 0.036)	0.136	-0.114 (-0.264, 0.036)	-2.48
Low IADL status					
	NSI	Reference	NA	NA	NA
	VI+HI	OR: 2.39 (1.17, 4.91)	0.017	0.10 (0.01, 0.19)	83.97
	OI+HI	OR: 2.10 (1.15, 3.91)	0.017	0.08 (0.02, 0.15)	69.17
Falls					
	NSI	Reference	NA	NA	NA
	VI+HI	OR: 0.54 (0.27, 1.04)	0.076	-0.09 (-0.18, 0.00)	-38.86
	OI+HI	OR: 0.82 (0.50, 1.35)	0.439	-0.03 (-0.11, 0.05)	-14.14
Hospitalisations					
	NSI	Reference	NA	NA	NA
	VI+HI	OR: 0.81 (0.28, 2.16)	0.687	-0.01 (-0.08, 0.05)	-16.79
	OI+HI	OR: 0.86 (0.39, 1.86)	0.698	-0.01 (-0.06, 0.04)	-12.60
Osteoporosis					
	NSI	Reference	NA	NA	NA
	VI+HI	OR: 1.33 (0.75, 2.31)	0.324	0.06 (-0.06, 0.17)	19.09

	OI+HI	OR: 1.00 (0.63, 1.59)	>0.99	0.00 (-0.09, 0.09)	0.19
Frailty					
	NSI	Reference	NA	NA	NA
	VI+HI	OR: 1.52 (0.64, 3.56)	0.335	0.04 (-0.04, 0.12)	35.32
	OI+HI	OR: 1.40 (0.70, 2.90)	0.346	0.03 (-0.03, 0.09)	28.05
Sarcopenia					
	NSI	Reference	NA	NA	NA
	VI+HI	OR: 1.18 (0.68, 2.04)	0.554	0.03 (-0.08, 0.15)	8.96
	OI+HI	OR: 1.23 (0.80, 1.88)	0.341	0.04 (-0.05, 0.13)	11.14

1. For PROs EQ-5D-5L, and life space mobility, the estimates are coefficients derived from linear regression models. The remaining PROs are odds ratios (OR) derived from logistic regression models. All models are adjusted for age, sex, ethnicity, low socioeconomic status, living alone, smoking status, polypharmacy and multimorbidity.

CI: Confidence Interval; DSI: Dual Sensory Impairment; EQ-5D-5L: EuroQoL 5-dimension 5-level; HI: Hearing Impairment; IADL: Instrumental Activities of Daily Living; NSI: No sensory impairment; OI: Olfactory Impairment; OR: Odds Ratio; PRO: Patient-Reported Outcome; VI: Visual Impairment

Table 5. Associations between DSI and costs using two-parts model.

Outcome	Exposure	First part		Second part		Overall marginal effect* (95% CI)
		OR (95% CI)	P-value	Cost Ratio (95% CI)	P-value	
Healthcare cost (in SGD)						
	Robust	Reference	NA	Reference	NA	NA
	VI+HI	0.70 (0.40, 1.21)	0.212	2.44 (0.79, 8.76)	0.120	280.68 (-325.12, 886.48)
	OI+HI	0.74 (0.49, 1.11)	0.146	2.04 (0.79, 5.31)	0.077	200.09 (-129.13, 529.31)

In the two-parts model, the first part results were odds ratios from logistic regression models and the second part results were cost ratios (exponentiated coefficients) from gamma generalised linear models with a log-link function for healthcare cost.

All models are adjusted for age, sex, ethnicity, low socioeconomic status, living alone, smoking status, polypharmacy and multimorbidity.

* The costs were shown in SGD. Based on the exchange rate of 1 SGD to 0.74515 USD on 31 Dec 2022, the USD equivalent costs were 209.15 and 149.10 for VI+HI and OI+HI, respectively.

CI: Confidence Interval; DSI: Dual Sensory Impairment; HI: Hearing Impairment; NSI: No Sensory Impairment; OI: Olfactory Impairment; OR: Odds Ratio; PRO: Patient-Reported Outcome; VI: Visual Impairment

Figure 1A. Sex-specific weighted prevalence of dual sensory impairment (DSI) subtypes

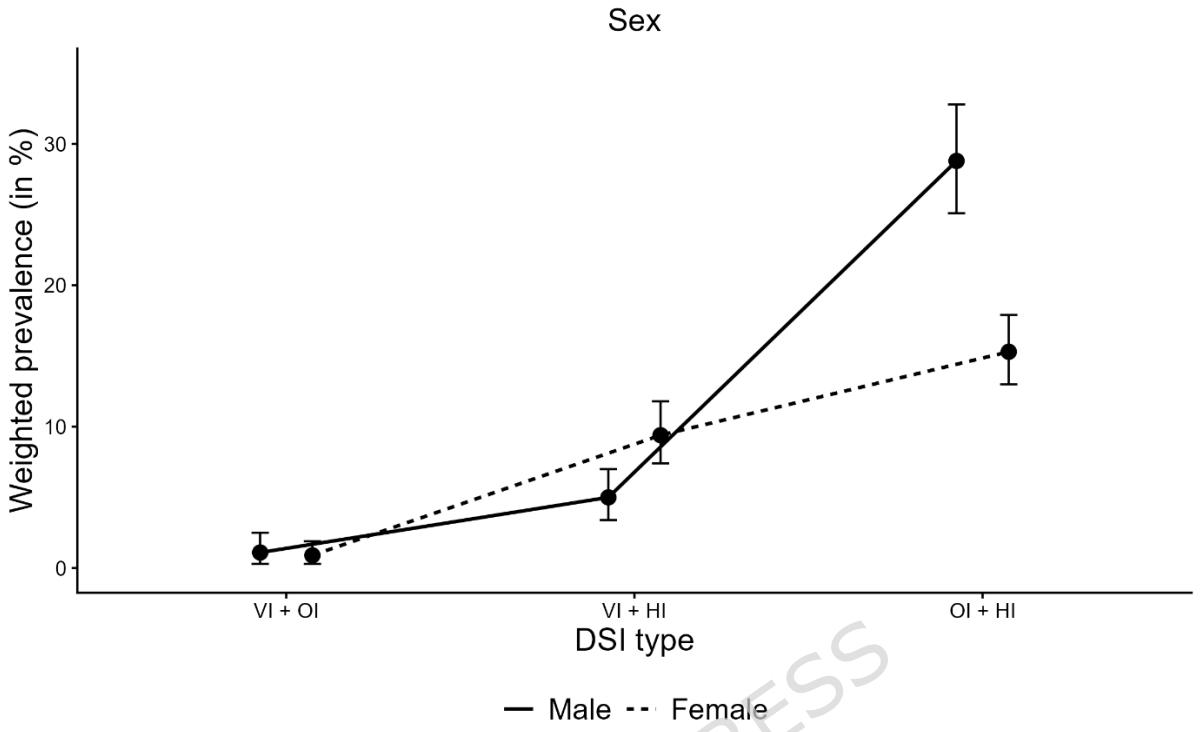

Figure 1B. Race-specific weighted prevalence of dual sensory impairment (DSI) subtypes