

Appendices

Appendix 1 - Detailed description of intervention iterations, study cohorts and data collection

Due to the research-through-design nature of the study, the intervention used in the study went through a process of iterative development. Participants were enrolled on four consecutive cohorts, aligning with four design and development cycles of the intervention. Each cohort received an updated version of the intervention incorporating the feedback of the previous cohorts. This appendix gives a detailed summary of the four design and development cycles and describes the four resulting iterations of the intervention.

Intervention

All iterations of the intervention featured 3 core elements;

1. A hardware kit of digital sensors and devices installed in the homes of participants to record various metrics related to their health,
2. An app for reporting this data back to the user,
3. supporting guidance for the participants to use the devices and interpret and respond to the data provided.

The hardware kit remained constant throughout iterations and is described in Table A. It included passive environmental sensors, installed around the participants home, and active sensors which the participant engaged with more directly.

Table A: Hardware sensor kit provided to all participants

Wearable / interactive sensors		Passives sensors		
				
Withings Scanwatch light	Withings Body Smart	Sonoff PIR motion sensors	Sonoff Temperature / humidity sensors	Sonoff Door sensors
				
Withings Sleep Analyser	Digital Dynamometer	Seed Studio mmWave Radar	M5Stack VL53L1X Time-of-flight sensor	Earzz Noise sensor

There were four iterations of the intervention (see Table B). The data from the digital sensors was displayed to the user via an app, which they accessed through a Samsung, which they accessed through a Samsung A9 tablet provided by the researchers. The first 3 iterations utilised the Withings application, which displayed data from the smartwatch, sleep analyser and smart scales of the same brand. The metrics shown were as follows:

Withings ScanWatch Light: Daily heart rate, Overnight heart rate, High & low heart rate notifications, Heart rate zones during workout, Active minutes, Steps, Calories burned.

Withings Body Smart Scales: Body weight, body fat, water percentage, muscle mass, bone mass and lean mass, visceral fat index, basal metabolic rate, and standing heart rate.

Withings Sleep Mat : Pneumatic data measuring breathing rate, heart rate. Sound sensor identifying audio signals specific to snoring & abnormal breathing. Metrics are Sleep duration, sleep onset and time to wake, Sleep apnoea episodes with severity classification, Sleep cycles (deep, light, REM phase), Continuous and average heart-rate, Snoring duration, Sleep Score.

The fourth iteration utilised a prototype application (“Healthy Habits”) designed by the researchers, reporting summary data from the smartwatch and sleep mat. The dynamometer had no bluetooth or wi-fi connectivity, so readings were recorded manually by participants on paper in the first three iterations and in the app in the fourth. Data from the passive sensors were available to participants via email on request.

All iterations featured a printed “participant manual” including information about the study and reminders of what participants should do while taking part. It also included explanations of each sensor, what data it recorded, and how it related to healthy ageing. In response to participant feedback during the first iteration that more context for the data was needed, subsequent iterations included further guidance on how to interpret the data and what actions users should take to improve their health. We chose to organise this guidance into seven “Healthy Habits” to better contextualise the data and to drive engagement, given habit formation is shown to be the most effective technique for individual health behaviour changeⁱ. Seven habits were chosen: step countⁱⁱ, sedentary timeⁱⁱⁱ, physical activity^{iv}, social connection^v, time in nature and sense of awe^{vi,vii}, strength and balance^{viii} and sleep^{ix,x}; based on the strength of existing evidence as an intervention for frailty, the ability to monitor the habit using the sensors used in the study, and anticipated uniqueness and universality of appeal. Supporting information, instructions on how to use their sensor data to set goals and track their progress, and suggestions for how to improve were given for each habit. This took the form of a printed booklet in iterations two and three and was incorporated into the Healthy Habits app in iteration four. The printed booklet was also given to the participants enrolled in the first cohort who chose to continue on the study. Participants were instructed to focus specifically on one particular habit each fortnight to try to improve in that habit and meet their goal.

Table B: Descriptions of the four iterations of the intervention

Intervention	Cohort	n	Description
Iteration 1	1	11	• Full hardware kits of sensors and devices described above. • Printed “participant manual” with information about the study, each sensor, what it measured and why it was important. • Withings app displaying data from the smartwatch, sleep analyser and smart scales • Printed healthy habits booklet (see iteration 2) once available.
Iteration 2	2	6	Iteration 1 with the addition of:

			Printed “Healthy Habits” booklet including information and prompts to choose one steps, active minutes, sedentary time, sleep, Strength & Balance, Nature & Awe, or Social activity to “focus on” improving each week.
Iteration 3	3	5	Iteration 2 with the addition of: - Revised printed Healthy Habits booklet, including updated copy and a new page explaining principles of habit formation and with an exercise to set an overall aim to accomplish during participation. - New video guide to supplement information in participant manual.
Iteration 4	4	8	- New researcher-designed prototype Healthy Habits app introduced, replacing Withings app and printed Healthy Habits booklet used in previous iterations - Healthy Habits app displayed data for Steps, Sedentary time, Active Minutes, and Sleep Habit, with additional detailed data, information and suggestions for the former two. - Healthy Habits app included a tasks page reminding participants of study tasks and to choose a new habit to focus on every fortnight.

Participant cohorts & feedback collection

Between April 2024 and February 2025 30 Participants were enrolled in one of four cohorts corresponding with each iteration of the intervention. The number of participants in each cohort were determined by availability of eligible applicants and were 11, 6, 5 and 8 for iterations 1, 2, 3 and 4 respectively. Enrolment of each cohort was separated by several months to allow for design and development.

Each participant was given a unique participant ID such as ‘DF01’ to pseudonymise their data. Qualitative data was gathered relating to the acceptability of, and attitudes towards the whole experience (which included: the installation visit, living with the sensors, using the technology and engaging with the intervention). Data was collected via online surveys and note-taking in response to semi-structured interviews and incidental comments during visits to the participants’ homes to install, maintain, and remove the sensors. This occurred at the starting, during and at the end of each participant’s involvement. See Table C for a description of each data collection point.

Table C: Descriptions of each data collection point and when they were completed

Time point	Method	Feedback collected
Installation visit	Semi-structured interview. Unstructured notes taken by researchers	Participants motivations for participating, interest levels in health and technology, description of current activity levels and habits. Incidental comments and questions by participant during installation visit.
2 days	Unstructured notes taken by researchers	First impressions of hardware kit and intervention. Questions or issues.
3 weeks	Semi-structured interview	Feedback on acceptability and usability of hardware kit and intervention, self-reported engagement, perceived utility, issues and suggested improvements.

6 weeks	Online survey	Feedback on experience of participation and usage of hardware kit and intervention including multiple choice and free-text answers.
6 months	Online survey	Feedback on experience of continued participation and usage of hardware kit and intervention including multiple choice and free-text answers.
End of participation (cohort 4)	Task-based usability testing of application with record of incidental comments	Feedback on specific elements of the app user experience and interface.

Appendix 2 - Code book used in qualitative analysis

Code	Description
Anxiety	Worries about specific readings or being reminded of poor health/weight
Capacity to change	Perception of one's ability to change their behaviour or their health based on the data they've seen
Comparison to others	Comments around comparison/contextualisation of user's own data to average for age or another individual's
Confidence	Wariness towards devices, resilience to unexpected events, willingness to explore/experiment/learn by doing, concern at getting something wrong
Confounding factors	Participants wanted to explain extenuating circumstances as to why they didn't hit a goal etc. illness, injury, weather, rest not being accounted for in the app
Data interpretation	Context for what is a healthy reading, what does this reading mean for me, what should I do with this info
Data quality/accuracy	Disagreements between sensors and/or lived experience, spurious recordings, doubts about clinical validity, concerns or questions about specific scenarios confounding data
Data to add	People asking for inclusion of additional metrics or health data
Engagement with data	How deeply people looked into detailed data and trends vs glancing at daily totals; "I don't need a sensor to tell me if I'm well/how much I've walked"; including mentions of becoming "more aware" of health but nothing further
Information delivery (human)	Preferences for how information is delivered in the app i.e. ignoring long text, asking questions in interviews, wanting to converse rather than research, "I don't want to read instructions". When and how people want to engage with their data
Motivation to participate	Reasons why people chose to take part in the study, what outcomes people hoped/expected to see, comments about contribution to research
Obsession	Admissions of obsessing over data OR derision of those who do
Peer support	Comment about interacting with other users or age-peers
Reactions to monitoring	How people felt towards being monitored or having sensors in their home (including intrusiveness of physical sensors, impact on home environment)
Reassurance	Comments about wanting flags of ill health or reassurance of good health
Recommendations for behaviour change	Reactions to tips and suggestions, opinions about goals, encouragement, personalised insights
Recognition of effort	Comments about activities not being captured by sensors/app and participants feeling short-changed/disenfranchised

Relevance to me	Comments about the program being suitable for older/other people (i.e. not the user) or whether specific elements were appropriate for them (e.g. Standardised question phrasing), information that isn't of interest
Reminders	Comments around watch notifications, nudges to change behaviours, re-set goals etc.

ⁱ Albarracín Det al. Determinants of behaviour and their efficacy as targets of behavioural change interventions. Nat Rev Psychol. 2024

ⁱⁱ Paluch AE, et al. Daily steps and all-cause mortality: a meta-analysis of 15 international cohorts. Lancet Public Health. 2022;7(3):e219–e228.

ⁱⁱⁱ Kehler DS, et al. A systematic review of the association between sedentary behaviors with frailty. Exp Gerontol. 2018;114:1–12.

^{iv} World Health Organization. Physical activity. Geneva: WHO; 2024. Available from: <https://www.who.int/news-room/fact-sheets/detail/physical-activity>

^v Holt-Lunstad J, Smith TB, Layton JB. Social relationships and mortality risk: a meta-analytic review. PLoS Med. 2010;7(7):e1000316.

^{vi} White MP, et al. Spending at least 120 minutes a week in nature is associated with good health and wellbeing. Sci Rep. 2019;9:7730.

^{vii} Stellar JE, et al. Positive affect and markers of inflammation: discrete positive emotions predict lower levels of inflammatory cytokines. Emotion. 2015;15(2):129–133.

^{viii} Cadore EL, et al. Effects of different exercise interventions on risk of falls, gait ability, and balance in physically frail older adults: a systematic review. Rejuvenation Res. 2013 Apr;16(2):105–114

^{ix} Sun XH, et al. Associations of sleep quality and sleep duration with frailty and pre-frailty in an elderly population: Rugao longevity and ageing study. BMC Geriatr. 2020;20:9.

^x Chaput JP, et al. Sleep duration and health in adults: an overview of systematic reviews. Appl Physiol Nutr Metab. 2020;45(10 Suppl 2):S197–S206.