Linking Physical Activity and Health:
A population study of elderly Icelandic men and women

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Thesis for the degree of Philosophiae Doctor

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Tengsl hreyfingar og heilsu:
Þýðisrannsókn á eldri körlum og konum á Íslandi

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Fyrir mömmu

Ágrip

Inngangur: Mikil fjölgun hefur orðið á eldra fólki í heiminum síðastliðin ár og er áætlað að árið 2050 verði eldra fólk um 22% af heildarfjölda ábúenda á jörðinni. Á Íslandi, þar sem um 329.000 manns búa, eru um 13,5% 65 ára eða eldri. Talið er að árið 2060 verði allt að 25% þjóðarinnar 65 ára og eldri. Áhættan á lífsstílssjúkdómum og skertri færni eykst með aldri, sem eykur álag á heilbrigðiskerfið. Hreyfing er skilgreind sem virkni líkamans sem verður vegna samdrátta í beinagrindarvöðvum og eykur orkunotkun. Hreyfing er mikilvægur áhrifaþáttur fyrir betri heilsu, en sýnt hefur verið fram á að hreyfing minnki með aldri um leið og kyrrseta eykst. Í þessari ritgerð er hreyfing, sem mæld er á hlutlægan hátt, skoðuð út frá fjórum sjónarhornum með fjórum rannsóknum, en hingað til hafa hlutlægar mælingar verið óalgengar á hreyfingu hjá eldra fólki. Fyrst er hreyfimynstri úrtaksins lýst í heild sinni og innbyrðis tengsl skoðuð. Ísland, sem þekkt er fyrir sérstæðar umhverfisaðstæður, gerir það áhugavert að skoða áhrif dagsljóss og hitastigs á hreyfingu eldra fólks og er það skoðað í annarri rannsókninni. Svefn breytist einnig með aldrinum, en mikilvægi svefns fyrir lífeðlisfræðilega og efnaskiptalega heilsu er vel þekkt. Í þriðju rannsókninni eru gæði svefns og tengsl hans við hreyfingu skoðuð. Margar rannsóknir hafa skoðað þá kenningu að aukin hreyfing sé tengd við minni heilarýrnun, en langtímasniðsrannsóknir eru sjaldgæfar. Með því að skilja betur sambandið á milli heilarúmmáls og hreyfingar, sem rannsakað er í fjórðu rannsókninni, væri hægt að skipuleggja áhrifaríkari íhlutanir sem hafa það að markmiði að hægja á heilarýrnun og auka lífsgæði eins mikið og kostur er. Með því að mæla hreyfingu, kyrrsetu og svefn hjá eldra fólki á Íslandi, myndaðist einstakt gagnasafn þar sem meðalaldur þátttakenda í Öldrunarrannsókn Hjartaverndar er mjög hár. Einnig hafa Íslendingar einna hæstu lífslíkur í heimi, sem gerir það enn áhugaverðara að rannsaka mikilvæga lífsstílsþætti eins og hreyfingu, kyrrsetu og svefn í þessu úrtaki.

Markmið: Megintilgangur rannsóknarinnar var að auka þekkingu á því hvernig hreyfing, kyrrseta og svefn tengist heilsu eldra fólks á Íslandi. Meginþráður þessara rannsókna var að nota einstakt safn mælinga í stóru, vel skilgreindu úrtaki eldra fólks á Íslandi sem voru þátttakendur í öðrum fasa Öldrunarrannsóknar Hjartaverndar, til að skilgreina hreyfingu, kyrrsetu og svefn hjá þeim. Einnig að nota þennan gagnagrunn til að kanna hvort rúmmálsbreytingar í heilanum væru tengdar hreyfingu og kyrrsetu.

Aðferðir: Frá apríl 2009 til júní 2010 lauk 649 þátttakandi, í öðrum fasa Öldrunarrannsóknar Hjartaverndar, sjö daga hreyfimælingum með hreyfimæli (ActiGraph GT3X). Mælirinn var staðsettur á hægri mjöðm þátttakenda. Aldur þátttakenda var á bilinu 73 til 98 ár. Almennt þýði úrtaksins innihélt 590 þátttakendur sem höfðu fjóra eða fleiri gilda daga af hreyfimælingum. Mælingum var einnig safnað fyrir 138 þátttakendur til að bera saman hreyfingu og kyrrsetu á mismunandi árstímum. Af þeim 590 þátttakendum sem höfðu gildar hreyfimælingar, fengu 244 svefnúr (Actiwatch Spectrum) til að bera í sjö daga og endurtóku 72 þátttakendur þær mælingar til samanburðar á mismunandi árstíðum. Þá voru gögn frá 352 þátttakendum nothæf í segulómhluta rannsóknarinnar. Í honum voru rúmmál gráa

og hvíta efnisins í heilanum við upphaf og rúmmálsbreytingar á fimm ára tímabili skoðaðar og tengsl þeirra við hreyfingu og kyrrsetu við lok fimm ára tímabilsins.

Niðurstöður: Kyrrseta var stærsti hlutinn af heildarnotkunartíma hreyfimælisins hjá þátttakendum, eða alls um 75%, en í kjölfarið kom mjög létt hreyfing með um 21% af heildarnotkunartíma hreyfimælisins. Hreyfing af miðlungs- eða mikilli ákefð var <1%. Karlar voru með örlítið meiri heildarhreyfingu (slög × dag^{-1}) en konur. Aldur hafði sterkustu tengslin við kyrrsetu (β= 0,36) sem og allar hreyfibreytur (β= -0,32 til -0,44). Konur eyddu meiri tíma en karlar í mjög létta hreyfingu (p< 0,001). Á sumrin var meiri tíma eytt í alla flokka hreyfingar, fyrir utan hreyfingu af miðlungs eða mikilli ákefð og kyrrseta var minni. Þversniðsrannsókn sýndi fram á að dagslengd spáði marktækt og sjálfstætt fyrir um svefnlengd, miðgildi tímasetningar svefns og fótaferðatíma (öll p<0,05). Hjá þeim sem endurtóku svefnmælingar höfðu karlar styttri svefnlengd (462±80 vs. 487±68 mín, p= 0,008), fyrri fótaferðatíma og fleiri raskanir á svefni um nótt en konur (46,5±18.3 vs. 40,2±15.7, p= 0,007). Hreyfing hafði lítil en marktæk áhrif á svefnseinkun og svefntíma (bæði p= 0,04). Meira grátt efni í heilanum (β= 0,11; p= 0,044) og hvítt efni (β= 0,11; p= 0,030) við upphafsmælingu var tengt við meiri heildarhreyfingu. Einnig þegar leiðrétt var fyrir upphafsgildum, var fimm ára breyting í gráa efninu (β= 0,14; p= 0,0037) og hvíta efninu (β= 0,11; p= 0,030) tengd heildarhreyfingu. Fimm ára breyting í hvíta efninu var tengd kyrrsetu (β= −0,11; p= 0,0007).

Ályktanir: Í þessari ritgerð er í fyrsta sinn gefin innsýn í hreyfi- og svefnmynstur eldra fólks á Íslandi sem mælt er á hlutlægan hátt. Sú niðurstaða að hreyfing er almennt lítil, virðist stangast á við langa lífslengd Íslendinga. Þær litlu breytingar á hreyfingu, svefnmynstri og svefngæðum sem koma fram í þessari rannsókn við mismunandi birtustig, gefur til kynna að Íslendingar hafa aðlagast vel þeim árstíðabundnu breytingum sem verða á birtustigi á landinu. Einnig er sýnt fram á langan svefntíma eldra fólks á Íslandi. Þar sem meðalaldur þjóðarinnar hækkar með hverju árinu, gæti verið mikilvægt að fá fólk til að hreyfa sig meira. Með því að fá fólk til að breyta um lífsstíl og hreyfa sig meira, gætu meiri möguleikar skapast fyrir það til þess að lifa sjálfstæðara lífi og auka lífsgæði á efri árum. Þetta er staðfest með þeim tengslum sem komu í ljós á milli hreyfingar, kyrrsetu og heilarýrnunar í rannsókninni. Frekari rannsókna er þörf til að kanna hvers vegna þetta úrtak eldra fólks á Íslandi lifir eins lengi og raun ber vitni, jafnvel þótt að það eyði megninu af vökutíma sínum í kyrrsetu.

Lykilorð:
Hreyfing, eldra fólk, kyrrseta, hreyfimælar, heilarýrnun, svefn, árstíðabreytingar.

Abstract

Introduction: Globally, the older adult population has increased substantially, and is estimated to reach approximately 22% of the world's population by 2050. In Iceland, with a total population of approximately 329,000, 13.5% are 65 years and older. By the year 2060, the proportion of older people will increase, and around 25% of the nation is predicted to be 65 years and older. As the risk of non-communicable diseases and disabilities increases with age, this provides a challenge for health and social care resources. Physical activity (PA) is defined as any bodily movement that is produced by the contraction of skeletal muscle and that substantially increases energy expenditure. PA is an important indicator of health, and overall PA level is known to decrease with age accompanied by increase in sedentary behavior (SB). In this thesis I address four aspects of objectively measured PA but objectively measured PA has been sparely used in older community dwelling persons. First, overall correlates and patterns of PA in the study group will be described. Iceland, which is known for its unique environmental conditions, is an interesting choice to study the effect of daylight and temperature on PA patterns in older adults and this constitutes the second study. Sleep is known to change with increasing age and its importance to physical- and metabolic health are also well known. In the third study, sleep quality is explored and its association with PA. Many studies have examined the hypothesis that greater participation in PA is associated with less brain atrophy, but longitudinal studies are rare. By understanding the relationship between brain volume changes and PA, which is examined in the last study, more effective intervention programs could be organized, with the aim to impede brain atrophies and keeping the quality of life as high as possible. By measuring the PA, SB and sleep in these older adults, a unique dataset will be obtained, because of the high mean age of the participants in study. Furthermore, Icelanders have one of the highest life expectancies in the world, making it interesting to examine important lifestyle factors, like PA, SB and sleep, in this cohort.

Objectives: The primary aim of the studies was to improve the understanding of how PA, SB and sleep contribute to health in older Icelanders. The common thread of these studies was to use a set of unique measurements in a large, well-characterized cohort of older people nested in the Age, Gene/Environment Susceptibility (AGES)-Reykjavik study, to define the behaviors of PA, SB, and sleep. Also, the rich database was used to examine if structural changes in the brain are associated with PA and SB.

Methods: From April 2009 to June 2010, 649 subjects of the second phase of the AGES-Reykjavik Study cohort (AGESII), aged 73–98 years wore an accelerometer (ActiGraph GT3X) at the right hip for one complete week in the free-living settings on seven consecutive days. The general population cohort included a total of 590 older adults who had at least 4 days of valid measurements during week-long measurements of PA. The measurements were collected twice for 138 of these participants to compare the PA and SB during different seasons. Of the 590 subjects that had valid PA measurements, 244 wore a sleep watch (Actiwatch Spectrum) for seven days and a subpopulation of 72 repeated the sleep watch measurements for seasonal comparisons. A sub-sample of 352 had sufficient PA and MRI data to be included in the MRI part of the study to look at the association of the

baseline and 5-year change in magnetic resonance imaging (MRI)-derived volumes of gray matter (GM) and white matter (WM) with PA and SB measured at the end of the 5-year period.

Results: In all subjects, sedentary time was the largest component of the total wear-time, 75%, followed by low-light PA (LLPA), 21%. Moderate-to-vigorous PA (MVPA) was <1%. Men had slightly higher average total PA (TPA) (counts × day^{-1}) than women. Age had the strongest association with SB (β= 0.36) and all PA variables (β= -0.32 to -0.44). The women spent more time in LLPA but less time sedentary and in MVPA compared with men (p< 0.001). During the summer, more time was spent in all PA categories, except for MVPA, and SB was reduced. Cross-sectional analyses revealed that day length was a significant independent predictor of sleep duration, mid-sleep, and rise time (all p<0.05). In those who repeated the sleep watch measurements, men had a shorter sleep duration (462±80 vs. 487±68 minutes, p= 0.008), earlier rise time, and a greater number of awakenings per night (46.5±18.3 vs. 40.2±15.7, p= 0.007), compared to women. PA had small, but significant impact on onset latency and bed time (both p= 0.04). More GM (β= 0.11; p= 0.044) and WM (β= 0.11; p= 0.030) at baseline was associated with more TPA. Also, when adjusting for baseline values, the 5-year change in GM (β= 0.14; p= 0.0037) and WM (β= 0.11; p= 0.030) was associated with TPA. The 5-year change in WM was associated with SB (β= −0.11; p= 0.0007).

Conclusions: In this dissertation, for the first time, insights of the PA and sleep patterns using objective measurements in healthy Icelandic older adults are established. The observation that the PA level was generally low in this population living at high latitude seems to contradict their longevity. The small changes in PA, SB, sleep patterns and quality observed during periods of disparate daylight length, suggest that this population is well adapted to the seasonal variation of daylight in Iceland. The long sleep time in the cohort is further revealed here. Although it is known to be important for older adults to remain active and exercise regularly to maintain good health, PA in older Icelanders is very low. As the population is getting older by every year, it may be important to intervene this trend of low PA and get older people to diminish their SB. By that, it is possible that they can live more independently and increase the quality of life in their older days. This is supported by the observed association between PA, SB and brain atrophy in the current study. Further researches are needed to address why this cohort of older adults live as long as they do, even they spend the majority of their day as sedentary.

Keywords:
Physical activity, older adults, sedentary time, accelerometry, brain atrophy, sleep, seasonal changes.

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Throughout my studies I have been privileged to learn from and work with exceptionally inspiring and thoughtful people. Their contribution to this thesis and my education is invaluable. First of all I would like to thank my hard working supervisor, Þórarinn Sveinsson, for giving me this opportunity and for the guidance and support through this process. I am yet to discover the limits of his patience, knowledge and understanding. Furthermore I would like to thank Vilmundur Guðnason for giving me the opportunity to work at the Icelandic Heart Association, where I learned the skills of conducting good research. The Icelandic Heart Association is a good environment to be in with plenty of professional, practical and experienced individuals. Thank you for making the data collection fun and interesting. I wish to express my sincere gratitude to Guðný Eiríksdóttir, who is always ready to help whenever needed. Jóhanna Eyrún Sverrisdóttir for teaching me to be more organized during the data collection and to Sigurður Sigurðsson for teaching me all about the brain measurements. I also want to thank Nína Dóra Óskarsdóttir and Elín Sandra Skúladóttir for their contribution to the data collection. The whole team in the Icelandic Heart Association is amazing. Special thanks to all those who participated in the accelerometry study, without their willingness and efficiency the data would have not been as good.

I wish to express my sincere gratitude to Kong Chen for his help throughout this process. He has been extremely helpful and willing to share his knowledge and experience which has served me incredibly well throughout this work. I would furthermore like to thank my co-authors of the papers; Annemarie Koster, Dane R. Van Domelen, Robert J. Brychta, Paolo Caserotti, Lenore J. Launer, Erlingur Jóhannsson and Tamara B. Harris, who are all outstanding scientists, for providing their useful contributions and comments. These papers would not exist without your help. My endless gratitude also goes to the participants of the studies as it goes without saying that without their contribution the research could not have been conducted. I would also like to give the Ph.D. committee thanks for their cooperation and help during the last few years, and everyone at the Research Center of Movement Science in the University of Iceland.

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Contents

List of abbreviations

AGES-Reykjavik study = Age, Gene/Environment Susceptibility Reykjavik Study

AGESII-Reykjavik study = Age, Gene/Environment Susceptibility Reykjavik Study, second phase

BMI = Body max index

CL = Confidence level

CSF = Cerebral spinal fluid

DSST = Digit symbol substitution test

FLAIR = Fluid-attenuated inversion recovery images

GM = Gray matter

HLPA = High-light physical activity

ICV = Intra-cranial volume

IQL = Inter quartile limits

LLPA = Low-light physical activity

LSPA = Lifestyle physical activity

MAP = Mean arterial pressure

MCI = Mild cognitive impairment

MD = Median value

MET = Metabolic equivalents

MNI pipeline = Montreal Neurological Institute pipeline

MMSE = Mini Mental State Examination

MRI = Magnetic resonance imaging

MVPA = Moderate to vigorous physical activity

MVPA 10+ = At least one bout ≥10 min of MVPA

NHANES = National Health and Nutrition Examination Survey

PA = Physical activity

SB = Sedentary behavior

SD = Standard deviation

SE = Standard error

SPA = Self-reported physical activity questionnaire

TPA = Total PA (counts × day^{-1})

WASO = Minutes of waking after sleep onset

WHO = World Health Organization

WM = White matter

WMH = White matter hyperintensities

WT = Wear-time

WT-PA = Wear-time adjusted PA (min × day^{-1})

Δ = 5-year change in GM and WM volumes calculated as the difference between the relative volume at endpoint and baseline

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I. Arnardottir NY, Koster A, Van Domelen DR, Brychta RJ, Caserotti P, Eiriksdottir G, Sverrisdottir JE, Launer LJ, Gudnason, V, Johansson E, Harris TB, Chen KY and Sveinsson T. Objective measurements of daily physical activity patterns and sedentary behaviour in older adults: Age, Gene/Environment Susceptibility-Reykjavik Study [*Age and Ageing*. 2013 Mar; 42(2): 222–229].

II. Arnardottir NY, Oskarsdottir ND, Koster A, Van Domelen DR, Brychta RJ, Caserotti P, Eiriksdottir G, Sverrisdottir JE, Launer LJ, Gudnason V, Johansson E, Harris TB, Chen KY and Sveinsson T. Comparison of summer and winter physical activity and sedentary behavior of senior citizens in the Reykjavík capital area: Age, Gene/Environment Susceptibility-Reykjavik Study [submitted for publication].

III. Brychta RJ, Arnardottir NY, Johannsson E, Wright E, Eiriksdottir G, Gudnason V, Marinac C, Davis M, Koster A, Caserotti P, Sveinsson T, Harris TB and Chen KY. Influence of day length and physical activity on sleep patterns in older Icelandic men and women [*Journal of Clinical Sleep Medicine* 2016 Feb. 12(2):203-13].

IV. Arnardottir NY, Koster A, Van Domelen DR, Brychta RJ, Caserotti P, Eiriksdottir G, Sveirrisdottir JE, Sigurdsson S, Johansson E, Chen KY, Gudnason V, Harris TB, Launer LJ and Sveinsson T. Association of change in brain structure to physical activity and sedentary behavior in older adults: Age, Gene/Environment Susceptibility-Reykjavik Study [*Behavioural Brain Research*; Volume 296, 1 January 2016, Pages 118–124].

Declaration of contribution

Below is a declaration of my contribution to each paper on which this thesis is based.

Paper I: I designed the study with my supervisor, Þórarinn Sveinsson. I participated in the data collection and performed all statistical analysis with the help of Þórarinn Sveinsson. I drafted the paper and participated in all revisions of the paper from co-authors.

Paper II: I designed the study with my supervisor Þórarinn Sveinsson and Nína Dóra Óskarsdóttir. I participated in the data collection and performed all statistical analysis with the help of Þórarinn Sveinsson. I drafted the paper and participated in all revisions of the paper from co-authors.

Paper III: The study was designed by Robert J. Brychta and Kong Y. Chen. I participated in the data collection and helped with drafting the paper and participated in all revisions of the paper.

Paper IV: I designed the study with my supervisor, Þórarinn Sveinsson, Tamara B. Harris and Lenore J. Launer. I participated in the data collection (the accelerometry part) and performed all statistical analysis with the help of Þórarinn Sveinsson. I drafted the paper and participated in all revisions of the paper from co-authors.

1 Introduction

Globally, the older adult population has increased substantially, and it is estimated to reach approximately 22% of the world's population by 2050 [1]. In Iceland, with a total population of approximately 329,000, 13.5% are 65 years and older. By the year 2060, the proportion of older will increase, so around 25% of the nation will be 65 years and older [2]. The risk of non-communicable diseases and disability increases with age, providing a challenge for health and social care resources [3].

Physical activity (PA) is defined as any bodily movement that is produced by the contraction of skeletal muscle and that substantially increases energy expenditure [4]. PA is an important indicator of health [5], but overall PA level is also known to decrease with age [6-8] accompanied by increase in sedentary behavior (SB) [9]. These changes have been shown to start in the forties [6], but after the age of 60, SB increases rapidly, possible due to positive factors such as increased leisure time following retirement, or negative factors such as worsening health conditions [9]. In old age, low PA has been linked with reduced physical functioning, such as mobility limitation [10], which is one of the most important factors in maintaining an individual's independence [11]. Sustained PA over the lifespan has been shown to have protective effects on mobility, even in those who start participating in PA at a later stage in life [12].

Although different measures exist for assessing overall energy expenditure (e.g. doubly-labelled water) and for the assessment of activity type and context (e.g. surveys and diaries), accelerometers are useful tools to explore patterns of PA objectively in terms of the elemental characteristics such as intensity, duration and frequency [13, 14]. An accelerometer is a small instrument worn by participants (see Figure 1) and it detects acceleration in selected planes and converts the data into "counts", which are then measured in specific time intervals or epochs. Higher counts result from greater acceleration. Accurate assessments of PA levels and patterns, using objective portable activity monitors as accelerometers and pedometers, have been shown to be sensitive and feasible for measuring general activity patterns in older adults [15]. Although the accelerometer has been used extensively to assess PA in other age groups [6], it has been sparsely utilized in older populations. The use of accelerometers is also the most valid and reliable method for evaluating SB [16, 17].

Figure 1: Accelerometer placed on the right hip. Reproduced from http://testing.actigraphcorp.com/

In epidemiological studies, PA has often been assessed by self-report measurements. Self-reports can be helpful, but tend to overestimate true PA and underestimate SB [18-20]. Accelerometry is a way to objectively assess PA that overcomes many of the limitations of self-reported measurements [21]. As an example, self-reported data from the 2005-2006 National Health and Nutrition Examination Survey (NHANES) indicate that 47% to 51% of adults aged 70 or older, met current US recommendations for PA [22, 23]. However, if based on objectively measured PA with an accelerometer, only 6% to 10% of adults aged 70 or older met current US recommendations for PA [23]. This misperception has been shown to be highly prevalent among specific subgroups of older persons [24] and may be due to over-reporting of PA because of difficulty recalling activities, cultural differences in interpretation, social desirability bias, or the way the questions are worded [20]. It has also been shown that light intensity PA is the most difficult intensity category to recall or remember accurately [22, 25, 26]. However, light PA is the most common intensity category for the activities in which older adults engage [19, 26, 27]. Questionnaire can be helpful in assessing the engagement in specific activity- and sedentary behaviors [17, 28, 29]. Recently, some improvements have been done on questionnaires to be able to assess SB. In a recent study by Visser and Koster [30] it was reported that a questionnaire including six sedentary activities (time spent napping, reading, listening to music, watching TV, hobby and talking to friends) was moderately associated with objectively measured SB. So if obtaining accelerometry data is not feasible, a questionnaire including six sedentary activities might enable persons to be ranked as having relatively low and relatively high level of SB, which is often important in epidemiological research [30].

To be able to understand PA in details, the PA is often segmented or compartmentalized into different intensity categories. In the literature, specific PA cut-points specialized for older people do not exist [31]. While reading and interpreting PA studies, it is important to be aware of which cut-points are used. Some studies have used lower cut-points for older adults [9, 14, 32], by e.g. defining light PA 100 to 1951 counts × min^{-1} and moderate-to-vigorous PA (MVPA) ≥1952 counts × min^{-1}. A few other studies [33, 34] defined, light PA as 100 to 1040 counts × min^{-1} and MVPA as >1040 counts × $minute^{-1}$, referring to three different sources [20, 32, 35]. Finding the most accurate cut-point to determine MVPA for older adults seems to be the most problematic, as cut-points from studies that included adults aged 60 or older, recommended MVPA cut points ranging from 574 to 2,020 counts × $minute^{-1}$ [6, 24, 36-39]. An accelerometer cut point that is set too high will result in an underestimation of MVPA. For some older adults, activities above the cut point of 6 metabolic equivalents (MET) that generally is used to indicate vigorous activity are not possible because of their declining maximal cardio-respiratory fitness [21]. As an example, in old age, light-intensity activities of 1.5–2.9 MET can be considered within the health-enhancing zone for those with low fitness level [40]. On average, for adults aged 65 to 79, moderate-intensity activity perceived as “somewhat hard” corresponds to 3.2 to 4.7 MET, and vigorous-intensity activity perceived as “hard” corresponds to 4.8 to 6.7 MET [41]. For adults aged 80 or older, moderate-intensity activity perceived as “somewhat hard” corresponds to 2.0 to 2.9 MET, and vigorous-intensity activity perceived as “hard” corresponds to 3.0 to 4.3 MET [21]. Given the lack of consistent MVPA cut points for older adults, Pruitt *et al.* [42] suggested that individualized approach may be necessary to determine the correct cut point, especially among people with low cardio-respiratory fitness.

In 2007, Cavanaugh *et al.* [43] developed a ‘bouts’ metric to quantify the number of activity epochs in a day, and using nonlinear, dynamical theory that represent random minute-to-minute fluctuations in activity. A bout is a continuous activity greater than a set threshold, e.g. a 10 min bout of MVPA defined as at least ten consecutive minutes of activity counts above the threshold ≥2020 counts × min^{-1}, often allowing one minute below the threshold (see Figure 2).

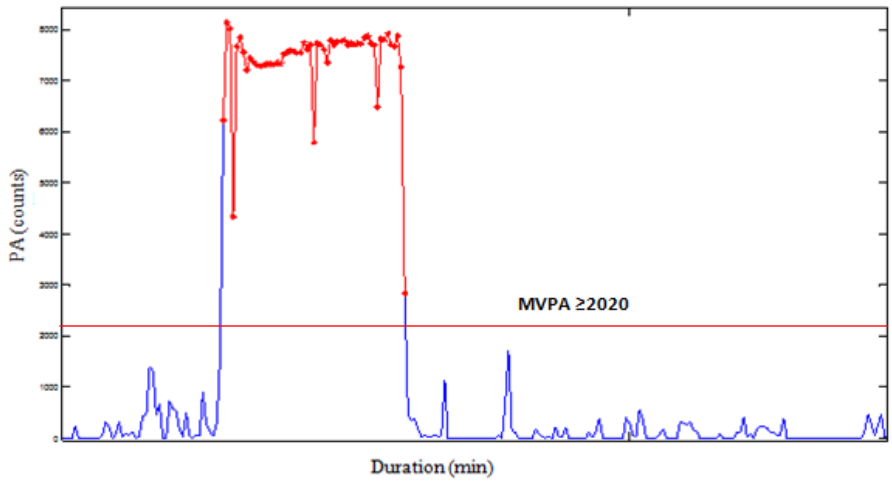

Figure 2: A bout of activity (in red).

The global recommendations on PA for both adults and older adults from the World Health Organization (WHO) [44], recommend a minimum of 150 min of at least moderate intensity PA per week for beneficial health effects, or at least 75 min of vigorous intensity PA throughout the week or an equivalent combination of those two intensity categories. Moderate PA is defined as considerable increases in heart rate and breathing, such as brisk walking (3-6 MET), but vigorous PA is even more exhausting (>6 MET) [45]. To make it easier to achieve the daily recommendation of PA, the activity can be performed in bouts of at least 10 min duration [44] and studies have supported this conclusion [46-49]. Many of older people are not reaching those 10 min bouts of MVPA [6, 50-52] and the proportion who fail to reach this goal increases by age, showing only 2.4% to 11.9% of older adults succeed [6, 23, 52, 53].

Increasing efforts have been made to understand how PA is linked to health in older individuals [21, 45]. As older individuals find it difficult to take part in and maintain high intensity PA [54, 55] it has been suggested by Buman *et al.* [56], that it may be more realistic to focus the recommendations for older individuals on replacing SB by “high-light” PA rather than on accumulating MVPA. Ortlieb *et al.* [52] showed that half of the time spent in MVPA was performed in bouts of one min and that almost half of the participants did not achieve at least one 10 min bout. They found that shorter bouts (e.g. 1 min bouts) of MVPA seem to provide more distinct evidence about the positive effect of MVPA on multi-morbidity and disability than longer bouts (e.g. 10 min bouts) [52]. Interestingly, other studies have shown that health benefits might also be gained with bouts of activity that last less than 10 min [49, 57] or by avoiding sitting and SB [58, 59].The role of light PA (e.g. self-care, cooking, light walking or shopping), measured by accelerometers, with regard to health effects has been less studied [52, 60, 61]. This might be of particular interest for older people who are limited in their exercise capacity due to age-related physical or mental restrictions [19].

As a part of total PA, during the last years, there has been growing interest in SB as a risk factor for adverse health effects [62-64]. SB is characterized by any waking activity that requires an energy expenditure ranging from 1.0 to 1.5 times the basal metabolic rate and a sitting or reclining posture [65]. SB includes sitting during commuting, in the workplace and the domestic environment and during leisure time [63]. Proxy measures as TW viewing, computer use and SB itself, has been shown to associate with many negative risk factors as cancer [66], obesity [67-69], type 2 diabetes [67], metabolic- and cardiovascular risk factors [70-77] and increased mortality [71, 78-81]. With increasing age, SB tends to increase as well, and it has been shown that the oldest adults (mean age around 80 years) spend 10 h × day^{-1} or more of their waking hours in SB [32, 34]. In Japan where life expectancy is the highest in the world, currently around 84 years [82], a recent research using tri-axial accelerometer showed Japanese older adults (mean age 72 years) appear to be quite active and only spending around 7.5 h × day^{-1} in SB [83]. In Norway, where life expectancy is currently 82 years [82], older adults (mean age 72 years) spent around 9.5 h × day^{-1} in SB [53]. In the United States, which has a bit lower life expectancies, a study by Buman *et al.* [56] showed older adults (mean age 75 years) spending over 9 h × day^{-1} in SB. The fact that the populations are progressively getting older has an enormous impact on the importance of the PA and SB in regards to the health paradigm.

In a study by Togo *et al.* [84], quadratic regression analysis showed an increase in daily average step counts in older adults over the ambient temperature range of –2 to 17◦C, but a decrease over the range of 17 to 29^{0}C. This was confirmed by Brandon *et al.* [85]. Studies have shown that both younger and older adults are more likely to be less active when the weather is bad [84, 86]. Increased precipitation, snow and wind, darkness and slippery conditions are common during the winter in Iceland which can influence outdoor PA pattern [84, 87-90] and thereby presumably increase time spent in SB at home. Studies have also shown that the length of daylight influences the total amount of PA, but those results varies between seasons and countries [84, 87, 89-93]. A few studies using objective measurements have shown older people to be less active during the winter [32, 94], but seasonal changes in PA are well known in younger adults [88, 90, 95-101].

The importance of sleep to physical and metabolic health is well documented [102-104]. Although sleep needs are thought to be independent of age [105], older people often have more sleep problems, such as premature awakening, fragmented sleep patterns [106], reduced sleep efficiency [107] and reduced depth of sleep [108]. The estimated prevalence of insomnia in elderly is thought to be around 40% [106, 109]. Poor sleep quality amongst older adults has been associated with declines in both physical- [110-112] and mental [103] function and increased risk of all-cause mortality [113]. Sleep initiation is controlled by the suprachiasmatic nucleus of the hypothalamus, an essential component of the master biological clock [114].

It has been suggested that greater sleep efficiency and lower fragmentation are associated with greater PA the following day in older women [115]. Increased PA is thought to lead to reduced sleep disturbances [116], improved sleep duration and quality and most studies have shown that exercise influences sleep regulation [117-119]. Many studies have reported that both shorter and longer than optimal sleep are associated with increased obesity, diabetes and other morbidities

related to energy balance [120, 121]. PA could possibly mediate the effects of sleep on energy balance related health outcomes [122-124]. Nevertheless, the relationship between sleep and PA remains poorly understood and only a few studies include objective measurements of PA in the analysis [104, 115]. Also, very few studies have simultaneously captured objectively measured sleep and PA data in older populations [115] and little is known about the interaction of day length and PA on sleep patterns in older individuals.

The brain atrophies with age due to volume loss in both white (WM) and gray matter (GM) and increase in white matter lesions [125]. GM has been shown to linearly decline with increasing age starting at early adulthood, while WM deterioration shows nonlinear changes [126-128]. WM has been shown to increase throughout adulthood, peaking at around the age of 40-60 years, followed by an accelerated decline starting around age 60 [126, 127]. Many studies have shown a positive relationship, between brain volumes on the one hand and PA or physical fitness on the other hand in older adults [129-132]. Longitudinal studies, using questionnaires have shown that higher level of PA at baseline predicts larger GM volume [133-135], larger WM volume [134] and greater total brain volume [134, 135] in late life. Also, blood flow in the brain has been shown to vary between types of exercise and intensities [136, 137]. Furthermore, it has been well documented that increased blood flow in the brain during exercises promotes the development of new neurons [138-140] and thereby delays brain structural and functional decline [141], making PA an important lifestyle factor in older adults. A few studies have shown a relationship between poor sleep quality and brain atrophy [107, 142, 143]. In a longitudinal study by Sexton *et al.* [107], poor sleep quality was associated with reduced volume within the superior frontal cortex and a greater rate of atrophy across the frontal, temporal, and parietal cortices [107].

1.1 Significance of the study

The Age, Gene/Environment Susceptibility-Reykjavik Study (AGES-Reykjavik study) has investigated the contributions of environmental factors, genetic susceptibility and gene – environment interactions to ageing of the neurocognitive, cardiovascular, musculoskeletal, body composition and metabolic systems in population with high life-expectancy [144]. The AGES-Reykjavik cohort was recruited from survivors of the Reykjavik Study. Data collection on the original Reykjavik study cohort dates back to 1967 and there have been two waves of data collection for the AGES-Reykjavik studies, separated by 5 years (AGES-Reykjavik in 2002–06 and the AGESII-Reykjavik study in 2007–11). Objectively measured PA, SB and sleep, using a seven-day free-living protocol, was included as part of the second phase of the Age, Gene/Environment Susceptibility-Reykjavik study (AGESII-Reykjavik study). By measuring the PA, SB and sleep in these older adults, a unique dataset was obtained, because of the high mean age of the participants in the AGESII-Reykjavik study. Furthermore, Icelanders have one of the highest life expectancies in the world [82], making it interesting to examine important lifestyle factors, like PA, SB and sleep, in this cohort.

At a latitude of 64-66°North, Iceland has a wide variation in daylight hours, 4-21 hours between winter and summer months, but much lower seasonal variation in temperature and

precipitation [145]. The variation in outdoor temperature and precipitation from summer to winter in Reykjavik is known to be slight relative to other locations of similar latitude. For instance, the variation in temperature in Reykjavik (average winter month of low of -3^{o}C and average summer month high of 13.3^{o}C, a range of 16.3^{o}C) is closer to that of San Francisco (37.8^{o}N with a low of 7.6^{o}C to a high of 21.2^{o}C high, range of 13.6^{o}C) than to Stockholm, Sweden (59^{o}N, -5^{o}C low to 22^{o}C high, a 27^{o}C difference) [145].

In Iceland, where environmental conditions are unique, it is of high interest to inspect how PA, SB and sleep patterns are related to these conditions. Based on these information, clearer recommendations could be given to older adults on how they could be active on times when or if activity tends to be lower than on a usual day. Additionally, little is known about the interaction of day length and PA on sleep patterns in older people. As sleep patterns changes with increasing age, it should also be interesting to see if the unique environmental conditions found in Iceland affect the sleep patterns in those older adults.

Magnetic resonance images (MRI) were taken twice with a five year interval, first in the AGES-Reykjavik study, and then five years later in the AGESII-Reykjavik study. This longitudinal design, provides an interesting opportunity to inspect the progress of brain atrophy in this cohort of elderly Icelanders, and how they are related to potential risk factors like PA and SB. It is important to understand this relationship in order to organize effective intervention programs with the aim to impede brain atrophy and keeping the quality of life as high as possible.

This study is the first to use accelerometers that record detailed free-living data over 7 days in a community-dwelling older population which represents the Icelandic population and will allow us to explore the linkages between PA, SB, sleep, and health in this age group. Moreover, it is the first research to simultaneously capture and analyze objectively measured PA, sleep and brain volumes measurements in an older population with high life expectancy, living at a latitude where the daylight change is dramatic between summer and winter months. Combined with comprehensive health and functional measures included in the both AGES studies, the data provide unique opportunity to address the knowledge gap in the areas of healthy aging and environmental influences.

2 Aims

The central goal of these studies was to improve the understanding of how PA, SB and sleep contribute to health in older Icelanders. The common thread of these studies was the unique objective and detailed measurements of free-living PA, SB and sleep in a large, well-characterized cohort of older people nested in the AGES-Reykjavik study. Also, to examine if structural changes in the brain are associated with PA and SB. The working hypothesis are: a) that PA, SB and sleep are influenced by, beside age and sex, environmental factors, b) that PA and SB are associated with the structural changes in the brain that can be identified by MRI.

The specific aims of each paper were as following:

Paper I: Implementation of objective measurements of daily PA patterns and SB in the cohort.
The aims of the study were to:

a) To assess free-living PA patterns in a subsample with waist-worn accelerometers.
b) To examine the features of PA and sedentary patterns with respect to age, sex and body mass index (BMI).

Paper II: Comparing summer and winter PA and SB in the cohort.
The aim of the study was to:
To explore the potential individual influences of environmental factors such as day-length and temperature on PA and SB through repeated measures.

Paper III: Investigating free-living sleep patterns in the cohort using wrist-worn actigraphy.
The aim of the study was to:
To delineate the potential effects of day length, objectively measured PA and other subject characteristics on sleep quality and patterns measured by wrist actigraphy cross-sectionally as well as within-individual.

Paper IV: Exploring linkages between changes in MRI-derived brain structure and PA and SB in our cohort.
The aim of the study was to:
Quantify the prospective changes in brain atrophy measurements, such as WM and GM volume changes, in a 5-year period and explore their association with objectively measured PA and SB.

3 Materials and methods

3.1 Study participants

The participants described in this thesis were older individuals selected from the second phase of the population-based AGESII-Reykjavik study, but measurements from the previous phase of the study, AGES-Reykjavik study were also used [144]. The study was planned and supported by the Intramural Research Program of the National Institute of Aging. During the PA measurement period, 1,194 subjects participated in the AGESII-Reykjavik study (73–98 years old). A flow chart for this study population is shown in Figure 3. For the PA measurements, 55 participants were excluded due to cognitive impairment (Mini Mental State Examination (MMSE) <20), 95 were excluded for other reasons (e.g. blindness and other physical obstructions), 84 refused and 294 did not participate because of scheduling conflict. Participants who obtained the score of ≥20 on the Mini Mental State Examination (MMSE) [146] received an accelerometer during the measurement period (April 2009 to July 2010). In the final dataset, the total of 649 had usable accelerometer data and 590 participants had four or more valid days (≥10 h of wear-time). Descriptive statistics for different sub-samples is shown in Table 1.

Subjects who had worn an accelerometer in the summer months, from May 15th to September 30th, 2009 were asked to wear the monitor again during winter, from November 18th, 2009 to March 19th, 2010. In total, 160 subjects (73.1%) accepted to repeat the measurements. Three device malfunctions led to 157 participants with usable accelerometer data, 138 of which had four or more valid days of measurements.

Sleep watches were given to 263 participants. A total of 244 participants had four or more valid days in the cross sectional period. Later a subsample of 72 subjects whose sleep measurement period began between August 1st, 2009 and October 1st, 2009 received sleep watches again to repeat the measurements of sleep and PA during a period with fewer daylight hours occurring between January 1st, 2010 and Mars 18th, 2010 (longitudinal study). Two accelerometer device failures occurred during the repeated measurement, leaving 70 subjects with valid sleep assessment and at least one valid day of accelerometry data during seasonal periods of greater and less hours of daylight.

For the MRI study, brain measurements and self-reported PA data were used both from the AGES-Reykjavik study and the AGESII-Reykjavik study, along with the accelerometry data. After excluding additionally those who did not have brain measurements at both time periods, those with mild cognitive impairment (MCI), dementia or scored ≤ 24 on the MMSE and ≤ 18 on the Digit symbol substitution test (DSST), the final number of subjects was 352.

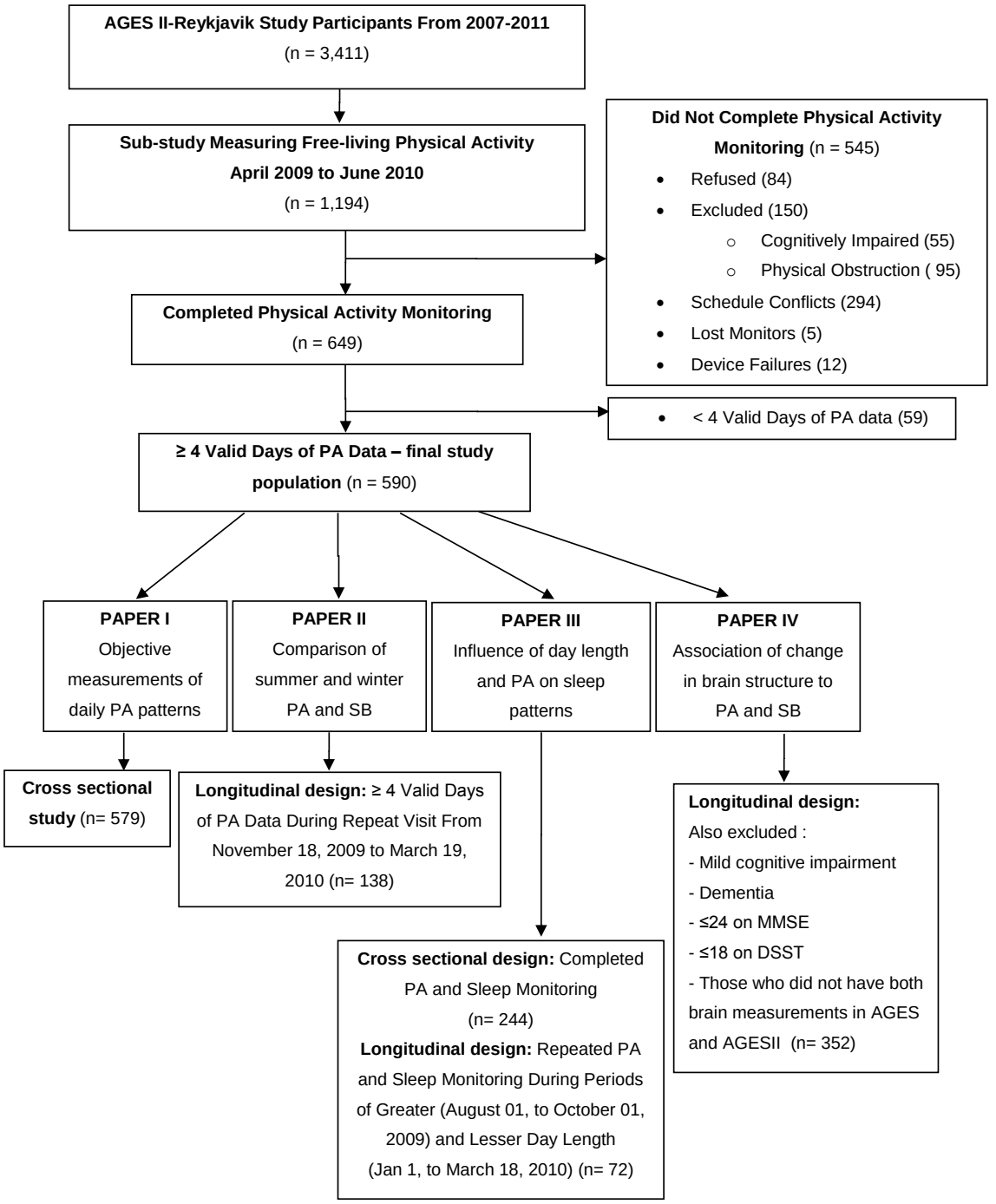

Figure 3: A flow chart for the final study population. PA= physical activity. SB= sedentary behavior.

Table 1: Descriptive statistics (mean and SD) for different sub-samples.

	Men		Women	
	N	Mean (SD)	N	Mean (SD)
Age (years)				
Non-receivers	179	81.8 (5.1)	283 (61.3%)	81.2 (5.4)
Cross sectional data (Paper I)	221	79.7 (4.2)	358 (61.8%)	80.2 (5.1)
Summer-winter data (Paper II)	55	80.5 (4.4)	83 (60.1%)	80.2 (5.2)
Sleep data (Paper III)	110	79.7 (4.6)	134 (54.9%)	79.4 (4.9)
Brain data (Paper IV)	137	79.2 (4.0)	215 (61.1%)	79.0 (4.6)
Weight (kg)				
Non-receivers	179	83.0 (13.6)	283 (61.3%)	70.8 (12.3)
Cross sectional data (Paper I)	220	83.2 (14.2)	357 (61.9%)	70.1 (13.6)
Summer-winter data (Paper II)	55	82.3 (12.0)	83 (60.1%)	71.5 (14.4)
Sleep data (Paper III)	110	82.7 (15.7)	134 (54.9%)	70.9 (14.3)
Brain data (Paper IV)	137	83.9 (13.6)	215 (61.1%)	70.9 (13.4)
BMI (kg/m^2)				
Non-receivers	179	26.7 (4.0)	283 (61.3%)	27.3 (4.6)
Cross sectional data (Paper I)	220	26.7 (3.9)	357 (61.9%)	26.8 (4.8)
Summer-winter data (Paper II)	55	26.5 (3.5)	83 (60.1%)	27.3 (5.1)
Sleep data (Paper III)	110	26.7 (4.4)	134 (54.9%)	27.2 (5.0)
Brain data (Paper IV)	137	26.9 (3.8)	215 (61.1%)	26.9 (4.7)

BMI= Body max index

3.2 Study design

The AGES-Reykjavik study is an epidemiologic study focusing on four biologic systems: vascular, neurocognitive (including sensory), musculoskeletal, and body composition/metabolism.

Paper I was a seven-day free-living protocol as part of a larger population-based longitudinal observational-cohort study, or the second phase of the AGES-Reykjavik study.
Paper II was a comparative study of summer-winter PA.
Paper III was a comparative study of summer-winter sleep pattern.
Paper IV was a longitudinal study of brain measurements and PA.

3.3 Outcome measures

In paper I, II and IV, the main outcome measure was PA and SB measured by accelerometer. In Paper III, the main outcome was sleep measured by a sleep watch.

3.3.1 Physical activity

PA was measured with accelerometry-based PA monitors (ActiGraph GT3X, Actigraph LLC, Pensacola, FL – see Figure 4) worn on the right hip and used to record PA intensity, computed as manufacturer specific activity counts in the vertical plane of motion, throughout the 7 day free-living

period (see Figure 1). Participants were told to remove the device before going to bed at night and before showering, bathing or other water activities and asked to record all non-wear events using a hand-written diary. Periods of non-wear were also automatically detected using a previously described method, 60 minutes or more of consecutive zero activity counts, allowing 1-2 minutes <100 activity counts [6]. A technician reviewed the diary and all detected non-wear periods with each participant using customized visualization software (Matlab version 2006, The Mathworks Inc, Natick, MA). An example of an activity output is shown in Figure 5. Days with less than 10 hours of wear-time were considered invalid [6]. In the current study, cut-points from Troiano *et al.* [6] and Matthews *et al.* [9, 149] are used. To explore the general patterns of PA, we only report the data in the vertical axis and present daily averages of (counts × valid day^{-1}) referred as Total PA (TPA), average wear-time (minute × day^{-1}), referred as wear-time, average intensity during wear-time (counts × min^{-1}), referred as WT-PA and time spent in different activity intensity categories. Activity intensity categories were defined as: Sedentary <100 counts × min^{-1}, Low-light PA (LLPA) >100 and<759 counts × min^{-1} (only used in Paper I), High-light PA (HLPA) >760 and <2019 counts × min^{-1} (only used in Paper I), Lifestyle PA (LSPA) ≥760 counts × min^{-1} (used in Paper II and IV) and MVPA ≥2020 counts × min^{-1}. A bout of MVPA was defined as at least ten consecutive minutes of activity counts above the threshold ≥2020 counts × min^{-1}, allowing for one minute below the threshold (only used in Paper I and II). A bout of LSPA was defined as at least five minutes of activity counts above the threshold ≥760 counts × min^{-1}, allowing for one minute below the threshold (only used in Paper II). In Paper II, we also explored each activity intensity category normalized by the wear-time (WT) or WT-PA, WT-LLPA, WT-LSPA and WT-MVPA, to adjust for variable wear-times on PA. Standard deviation (SD) variables (SD-wear-time, SD-SB, SD-TPA, SD-LLPA, SD-LSPA and SD-MVPA) were calculated as SD of the day-to-day variation in respective activities.

Figure 4: ActiGraph GT3X. Reproduced from www.actigraphcorp.com

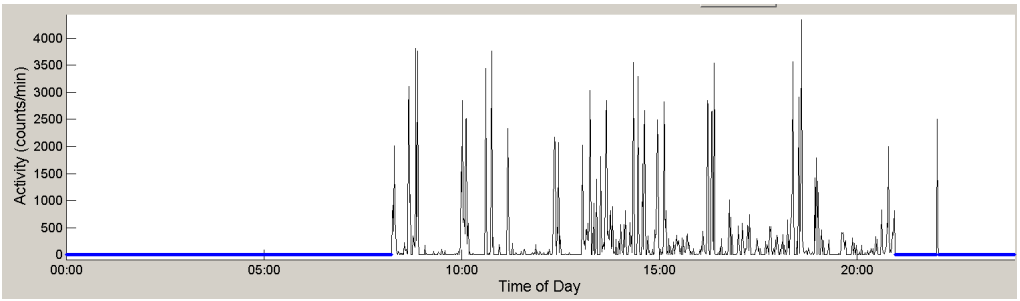

Figure 5: Example of an activity output for one day.

3.3.2 Sleep measurements

Participants were given actigraphy-based sleep watches (Actiwatch Spectrum, Phillips-Respironics, Bend OR – see Figure 6) to wear on the non-dominant wrist for 7-day free living sleep assessment. The watch contains motion-sensitive accelerometers which have been previously validated for objective sleep measurement [147]. Each watch was programmed to record wrist-activity and white-light intensity in 15 s epochs. Rest and sleep periods were automatically identified using the manufacturer software [148] (Actiware version 4.0) and visually inspected and compared to the hip PA monitor non-wear events and the hand-written sleep diary that each subject kept. The following parameters were recorded for each sleep event over the 7-day period using the Actiware software [148]: bed time (start of rest period, time subject gets in bed), rise time (end of rest period, time subjects gets out of bed), rest duration (rise time minus bed time), sleep duration (time within the rest period that was scored as sleep), onset latency (sleep onset time minus bed time), number of awakenings during sleep period, minutes of waking after sleep onset (WASO), mid-sleep time (midpoint between bed time and rise time), and sleep efficiency (percent of rest period that participant was scored asleep). Further, the white light intensity was averaged over each complete day and for each rest and sleep period. An example of a sleep watch output is shown in Figure 7. Fifty three different sleep watches were used over the course of the study.

Figure 6: Actiwatch Spectrum. Reproduced from www.usa.philips.com

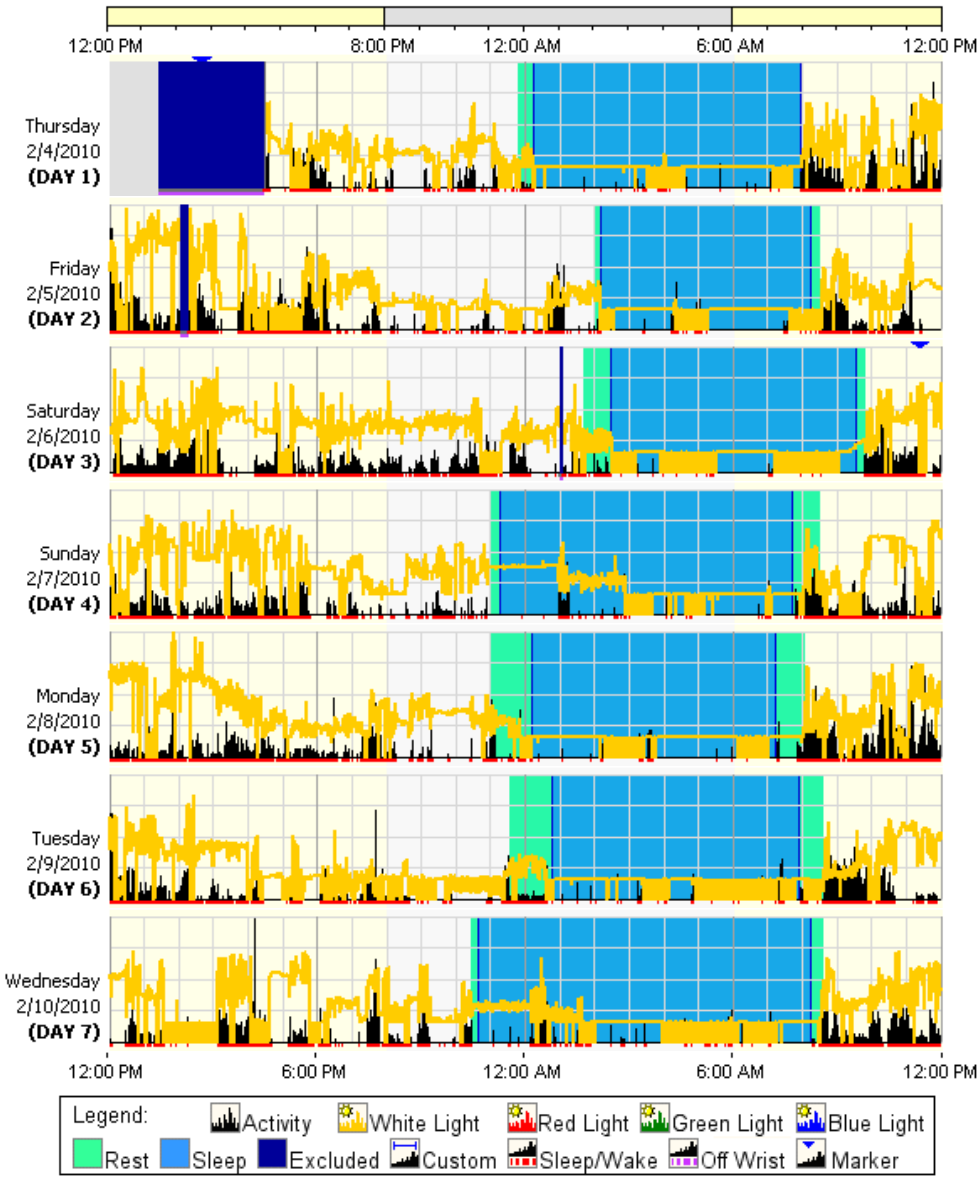

Figure 7: Example of a sleep watch output for one day. Yellow lines show the lux value measured by the light sensor and the black lines show activity.

3.4 Predictors

In Paper IV, the brain measurements, GM and WM, were use to predict the PA and SB five years later.

3.4.1 MRI measurements

MRI including T1-, proton density-, and T2-weighted and fluid-attenuated inversion recovery (FLAIR) images were acquired on a 1.5-Tesla Signa Twinspeed EXCITE system (General Electric Medical Systems, Waukesha, WI) in the AGES-Reykjavik study. Brain tissue volumes, including GM, WM, cerebral spinal fluid (CSF), and white matter hyperintensities (WMH), were generated separately, using the multispectral MR images and a high-throughput automatic image analysis pipeline, which is based on the Montreal Neurological Institute (MNI) pipeline and optimized for use in the AGES-Reykjavik study [125]. The key processing stages were as follows: stereotaxic registration was achieved after signal non-uniformity correction by an affine transformation of the T1-weighted images to the ICBM152 template. Inter-sequence registration was performed by registering images from the individual (T2/proton density, fluid-attenuated inversion recovery) sequences to the T1-weighted images in order to accurately align all image volumes acquired during an acquisition session. Linear signal intensity normalization was then applied to correct for signal intensity variations across images in the different sequences. Finally, tissue classification was achieved with an artificial neural network classifier. The absolute volumes of the four tissue types were subsequently calculated and converted to native space volumes using the scale factor obtained from the stereotaxic registration transformation. Intra-cranial volume (ICV) was calculated by adding the volumes of GM, normal WM, WMH and CSF. All tissue volumes are presented as percent of the total ICV. The acquisition and post-processing of the MRI have been described in detail elsewhere [125]. The methods used in the follow-up MRI were the same as used in the baseline measurements. The change (Δ) in GM and WM volumes was calculated as the difference between the relative volume at follow-up and baseline.

3.3 Statistical analysis

IBM SPSS 19.0 and 20.0 (Papers I and IV), SAS 9.4 (Paper II) and the Matlab program and R version 3.1.0 (Paper III) were used for statistical analyses and a p value of ≤0.05 was considered significant for all analyses.

Paper I: To adjust for the skewness when comparing data between different age and BMI groups, all parametric statistical tests were conducted on square root transformed data with back transformation for presentation of results. Independent t-test was used to determine difference between sexes in age, weight, BMI and PA variables. Multiple linear regression models were used to test the effect of age and BMI on PA. Factorial ANOVA for repeated measures was used to test the within-day variation of PA, using Greenhouse-Geisser correction for lack of sphericity. For *post hoc* analysis of interaction between within-day variation of PA and sex, independent t-test with Bonferroni correction was used to test sex difference for each day hexile. Factorial ANOVA was used to compare PA between different days of the week, using Tukey HSD for *post hoc* analysis.

Paper II: To adjust for the skewness, PA variables were square root transformed and all parametric statistical tests were conducted on transformed data (all average numbers in texts, tables and graphs were produced from original data). Wear time was used to normalize for device wear time in WT-LLPA, WT-LSPA, WT-MVPA, WT-TPA and SB. A mixed model ANOVA was used to explore the association between the accelerometer variables and age, sex, BMI, health status, temperature and day length. The standard β values were used to compare the relative strength of contributions by each variable to PA. Due to high frequency of zeros, paired, nonparametric comparisons (Wilcoxon Signed Rank test) were used to test for seasonal difference in the number of bouts, accumulated minutes of bouted activity, and total counts accumulated in ≥5 min bouts of LSPA and ≥10 min of MVPA. Wilcoxon test was also used to compare the accumulated min and counts between low- and high active participants. Wilcoxon test was used to compare summer to winter change between groups (sex and low vs. high active participants; group-season interaction). Results of the bouted activity are presented as lower quartile, median value (MD) and upper quartile. Low- and high active participants were separated by the median of average TPA for summer and winter. McNemar´s test was then used to compare summer and winter proportions of participants who had at least 1 bout of ≥5 min LSPA and ≥10 min MVPA. Chi-Square test was used to compare groups.

Paper III: For the cross-sectional analysis, Spearman correlations were used to identify potential relationships between sleep measures, subject demographics, and PA measures. To preserve sufficient power, only those measures achieving Spearman correlation coefficients with the significance ($p<0.05$) were selected to enter the stepwise, multivariate regression to further explore the relationship between sleep parameters, gender, PA, and day length. Separate multiple linear regression models were evaluated using sleep duration, rest duration, sleep efficiency, onset latency, WASO, number awakenings, and sleep midpoint time as independent response variables while age, sex, BMI, self-reported health status, total activity counts per wear-time minute, outdoor temperature, diagnosed depression, and day length were used as covariates in each of the regression models. The use of antidepressant, benzodiazepines, and all other sleep medications were combined into one variable and used as a covariate in the regression models. Backward-elimination regression analysis was used to identify significant, independent predictors for each of the sleep parameters listed. Covariates with significance at or below 0.10 were retained during each step of the analysis.

For the within-individual visits, comparisons between the environmental and PA variables acquired during periods of long and short day lengths were performed using paired t-tests. Linear mixed models with random intercepts were used to compare sleep parameters collected over two measurement periods separated by 147±18 days on average. Each sleep parameter served as a response variable in separate models. Subject identification was the random effects variable in each model. Other covariates of BMI, age, gender, self-reported health status, diagnosis of depression, sleep medication usage, and day length were included as fixed effects variables in each model.

Paper IV: The association between the accelerometer variables and brain volume measurements was analyzed using linear regression models. The PA variables were log transformed to correct for skewness. For Tables 13 and 14, linear regressions were performed and several models were formed.

First, Model 1 was adjusted for age and sex and coefficients reflect association for individual brain volume measurements variables in separate models. In Model 2 each brain volume variable was adjusted for age, sex, brain infarcts, days between baseline and follow-up measurements, self-reported PA questionnaire (SPA), BMI, depression, mean arterial pressure (MAP), type 2 diabetes, smoking status and education. Further, in Model 3, all baseline measurement variables and 5-year change variables were entered in the same model adjusted for same covariates as in Model 2.

4 Results

4.1 The study cohort

The general population cohort (Paper I) included a total of 579 who had at least 4 days of valid measurements during a week-long measurements of PA. Detailed demographic and anthropometric characteristics of subjects for Paper I are presented in Table 2. The mean age of the women was 79.7 (SD= 4.2) and the men 80.2 (SD= 5.1). Participants who wore the accelerometers had similar subject characteristics compared with those participants who did not receive an accelerometer.

Table 2: Descriptive statistics for subjects with four or more days with 10 or more hours of wear-time in Paper I. Genders compared by t-test; for PA and sedentary variables t-tests were conducted on square root transformed data. PA measured by sex, age group and BMI. For cut-points see Troiano et al. [6] and Matthews et al. [9, 149].

	Men		**Women**		
	n	**Mean (SD)**	**n**	**Mean (SD)**	**p**
Wear-time (min × day^{-1})	221	832 (92)	358	815 (83)	**0.024**
TPA (1000counts × day^{-1})	221	117 (68)	358	105 (58)	**0.048**
WT-PA (count × min^{-1})	221	139 (78)	358	128 (65)	0.092
SB (hours × day^{-1})	221	10.5 (1.5)	358	10.0 (1.3)	**<0.001**
SB% (percent × weartime^{-1})	221	75.9% (8.3%)	358	73.9% (8.6%)	**0.001**
LLPA (min × day^{-1})	221	163 (55)	358	182 (60)	**<0.001**
HLPA (min × day^{-1})	221	29 (22)	358	27 (23)	0.23
MVPA (min × day^{-1}) [a]	221	9.9 (13)	358	5.0 (7.2)	**<0.001**

PA= Physical activity; TPA= Total PA (counts × day^{-1}); WT-PA= wear-time adjusted PA; SB= Sedentary behavior (0-99 counts × min^{-}1); SB%= SB adjusted for wear-time; LLPA= Low-light PA (100-759 counts × min^{-1}); HLPA= High-light PA (760-2019 counts × min^{-1}); MVPA = Moderate- to-vigorous PA (≥2020 counts × min^{-1}). *a*= Of the 579 participants, 25 (4.3%) had zero minutes of MVPA, 10 (4.5%) men and 15 (4.2%) women. Significant difference between genders (p<0.05) is bolded.

Descriptive statistics for the subpopulation of the 138 individuals, who had at least 4 days of valid measurements during week-long PA measurements during both summer and winter (Paper II), are displayed in Table 3. The mean age of the participants was 80.3 years (SD= 4.9) with a range between 73 to 91 years (60.1% women). Self-reported health status (1-excellent, 5-poor) was 2.6 (SD= 1.2).

Characteristics of the 244 participants that had a week long measurements of PA and sleep (Paper III), are presented in Table 4. The mean age was 79.5 years (SD= 4.8) years. Over 70% of the participants self-reported to be in good health or better while less than 3% of participants reported to have poor health-status. Over a third of the subject (38%) reported using medications known to induce sleep including antidepressants, benzodiazepine, and other sleep medications, and usage was higher in women (44%) than in men (27%). However, no relationship was found between the use of sleep medication and hours of daylight during the study. The mean age for the 72 individuals who repeated

the week long PA and sleep measurements during periods of longer (13.4 ± 1.4 hrs) and shorter day length (7.7 ± 1.8 hrs, p<0.001), was 80.1 years (SD= 5.1), see Table 5.

Descriptive statistics for the 352 women and men that had their PA measured for 7 days and MRI measurements from both AGES-Reykjavik study and the AGESII-Reykjavik study are presented in Table 6. Participants were also subdivided into those with high (above median) and low (below median) baseline volumes of both GM and WM. TPA and SB for men and women, for low and high GM, and for low and high WM, are presented in Figure 8 and Figure 9, respectively. The mean age was 79.1 years (SD= 4.4).

Table 3: Demographic, environmental and activity parameters (mean and SD) for sub-group of participants with repeat visits during summer and winter (Paper II).

	Summer		**Winter**	
	Men	**Women**	**Men**	**Women**
N	55	83	55	83
Environmental				
Average Day Length [h:min × day $^{-1}$]	15:26 (2:51)	14:41 (2:38)	7:26 (2:04)	7:16 (1:55)
Average Temperature, ^{o}C	8.4 (2.3)	8.6 (2.5)	2.7 (2.5)	2.5 (2.7)
PA parameters				
Wear-time [min × day^{-1}]	836 (79)	819 (74)	815 (75)	805 (67)
SD-Wear-time [min × day^{-1}]	71.2 (35.5)	65.2 (29.7)	79.2 (32.2)	70.4 (31.6)
SB [h:min × day^{-1}]	10:29 (1:25)	10:07 (1:16)	10:43 (1:21)	10:13 (1:18)
WT-SB [percent of wear-time]	75.4 (9.4)	74.3 (8.9)	78.9 (8.1)	76.2 (8.5)
SD-SB [h:min × day^{-1}]	1:18 (0:35)	1:08 (0:31)	1:20 (0:29)	1:10 (0:30)
TPA [x1000 counts × day^{-1}]	118 (83)	106 (60)	99 (66)	89 (46)
WT-TPA [counts × min^{-1}]	140 (98)	128 (67)	122 (83)	110 (55)
SD-TPA [x1000 counts × day^{-1}]	44 (39)	33 (21)	36 (32)	28 (21)
LLPA [h:min × day^{-1}]	2:48 (1:02)	2:58 (1:02)	2:21 (0:52)	2:48 (1:01)
WT-LLPA [percent of wear-time]	19.9 (6.7)	21.6 (6.6)	17.3 (5.9)	20.8 (7.0)
SD-LLPA [h:min × day^{-1}]	0:38 (0:21)	0:35 (0:17)	0:32 (0:21)	0:35 (0:15)
LSPA [h:min × day^{-1}]	0:40 (0:37)	0:34 (0:28)	0:31 (0:27)	0:24 (0:18)
WT-LSPA [percent of wear-time]	4.70 (4.46)	4.09 (3.28)	3.80 (3.42)	2.99 (2.15)
SD-LSPA [h:min × day^{-1}]	0:21 (0:18)	0:17 (0:13)	0:15 (0:14)	0:12 (0:09)
MVPA [h:min × day^{-1}]	0:09 (0:16)	0:05 (0:06)	0:09 (0:13)	0:04 (0:07)
WT-MVPA [percent of wear-time]	1.07 (1.88)	0.61 (0.76)	1.07 (1.64)	0.49 (0.83)
SD-MVPA [h:min × day^{-1}]	0:07 (0:10)	0:05 (0:05)	0:06 (0:08)	0:04 (0:07)

PA= Physical activity; SB= Sedentary behavior; TPA= Total PA; SD= Standard deviation, daily variation in each PA/SB; WT-… = Physical activity variables normalized for wear time; LLPA= Low-light PA (100-759 counts × min^{-1}); LSPA= Lifestyle PA (≥760 counts × min^{-1}); MVPA= Moderate- to-vigorous PA (≥2020 counts × min^{-1}).

Table 4: Demographic, environmental, activity, and sleep parameter for cross-sectional population of older Icelandic adults (Paper III). Data are presented as mean ± standard deviation [range] or percentage of participants.

	All	**Men**	**Women**	**p**
	244	110	134	
Demographic and Environmental				
Self-Reported Health (1-excellent, 5-poor)*	2.6 ± 1.2 [1.0 - 5.0]	2.5 ± 1.2 [1.0 - 5.0]	2.7 ± 1.2 [1.0 - 5.0]	0.13
Anti-depressant Usage (%)	11.1	10.0	11.9	0.63
Benzodiazepine Usage (%)	11.9	9.1	14.2	0.22
Other Sleep Medication Usage (%)	24.2	15.5	31.3	**<0.01**
All Sleep Medication/Anti-depressant Usage (%)	37.7	27.3	43.6	**<0.01**
Diagnosed Depression (%)*	4.60	3.80	5.30	0.6
Daylight, hrs	10.3 ± 3.1 [4.4 - 16]	10.3 ± 3.0 [4.6 - 15.9]	10.3 ± 3.2 [4.4 - 16.0]	0.97
Outdoor Temperature (^{o}C)	4.9 ± 3.5 [-3.1 - 11.3]	4.5 ± 3.6 [-3.1 - 11.3]	5.2 ± 3.4 [-2.3 - 11.3]	0.09
Daily Average White Light Exposure (Lux)	158.9 ± 177.7 [3.4 - 984.5]	165.2 ± 182.6 [3.4 - 984.5]	153.8 ± 174.2 [3.7 - 826.8]	0.62
Rest Time White Light Exposure (Lux)	23.3 ± 45.9 [0.0 - 303.4]	21.1 ± 41.5 [0.0 - 220.8]	25.1 ± 49.4 [0.0 - 303.4]	0.50
Sleep Time White Light Exposure (Lux)	21.0 ± 45.6 [0.0 - 300.4]	19.0 ± 41.2 [0.0 - 220.1]	22.6 ± 49.0 [0.0 - 300.4]	0.55
Activity Measures				
Wear-time (>10hrs, n)	6.3 ± 0.9 [4 - 7]	6.4 ± 0.9 [4.0 - 7.0]	6.3 ± 0.9 [4.0 - 7.0]	0.57
Wear-time (min)	830.2 ± 94.1 [641.5 - 1343.4]	835.2 ± 95.6 [645.5 - 1212.5]	826.1 ± 93.0 [641.5 - 1343.4]	0.45
TPA (1000counts × day^{-1})	109.0 ± 56.3 [14.2 - 349.7]	112.5 ± 58.5 [14.2 - 349.7]	106.1 ± 54.5 [19.5 - 288.2]	0.38
WT-PA (counts × min^{-1})	130.7 ± 65.1 [21.1 - 453.1]	133.9 ± 69.6 [21.1 - 453.1]	127.2 ± 61.9 [27.1 - 319.9]	0.43
Sleep Measures				
Sleep Intervals (n)	7.0 ± 0.5 [5.0 - 12.0]	7.1 ± 0.7 [5.0 - 12.0]	7.0 ± 0.4 [6.0 - 10.0]	0.22
Rest Duration (min)	544.9 ± 67.4 [276.4 - 764.4]	529.4 ± 72.4 [276.4 - 764.4]	557.6 ± 60.4 [416.3 - 740.3]	**<0.01**
Sleep Duration (min)	475.5 ± 74.5 [190.7 - 741.8]	461.7 ± 79.9 [210.0 - 741.8]	486.9 ± 68 [190.7 - 662.1]	**<0.01**
Onset Latency (min)	37.1 ± 31.5 [1.2 - 208.2]	34.4 ± 28.7 [1.3 - 157.6]	39.3 ± 33.6 [1.2 - 208.2]	0.18
Sleep Efficiency (%)	81.6 ± 9.9 [36.5 - 99.2]	80.9 ± 10.1 [48.0 - 99.2]	82.2 ± 9.8 [36.5 - 97.2]	0.34
Waking after sleep onset (WASO) (min)	31.3 ± 17.3 [0.9 - 148.9]	33.0 ± 20.4 [0.9 - 148.9]	30.0 ± 14.3 [8.8 - 95.6]	0.18
Number of Awakenings (n)	43.1 ± 17.2 [1.0 - 104.0]	46.5 ± 18.3 [1.0 - 104.0]	40.2 ± 15.7 [10.7 - 89.4]	**<0.01**
Bed Time (hh:mm ± min)	23:28 ± 61.9 [19:49 - 03:49]	23:23 ± 55.9 [20:15 - 01:44]	23:33 ± 66.3 [19:49 - 03:49]	0.24
Rise Time (hh:mm ± min)	08:35 ± 64.2 [05:11 - 11:51]	08:15 ± 69.5 [05:11 - 10:45]	08:51 ± 54.6 [05:59 - 11:51]	**<0.01**
Mid-Sleep Time (hh:mm ± min)	04:43 ± 34.2 [03:12 - 07:17]	04:33 ± 34.1 [03:12 - 06:22]	4:51± 31.9 [03:35 - 07:17]	**<0.01**

PA= Physical activity; TPA= Total PA (counts × day^{-1}); WT-PA= wear-time adjusted PA (counts × min^{-1}). *N =240 (All), 107 (Men), 133 (Women) for self-reported health status and diagnosed depression. Significant difference between genders ($p<0.05$) is bolded.

Table 5: Demographic, environmental, activity, and sleep parameters for sub-population of participants with repeat visits during periods of longer and shorter day length (Paper III). Data are presented as mean ± standard deviation [range] or percentage of participants.

Demographics at first visit		**Demographics at first visit (continued)**	
n	72 (26M, 46F)		
Age (yr)	80.1 ± 5.1 [73 - 94]	Anti-depressant Usage (%)	13.9
Height (cm)	166.8 ± 8.5 [149.0 - 189.0]	Benzodiazepine Usage (%)	18.1
Weight (kg)	74.9 ± 14.4 [44.0 - 115.0]	Other Sleep Medication Usage (%)	25.0
BMI (kg/m^2)	27.0 ± 5.0 [17.0-42.8]	All Sleep Medication/Anti-depressant Usage (%)	43.1
Self-Reported Health (1-excellent, 5-poor)	2.6 ± 1.2 [1.0-5.0]	Diagnosed Depression (%)	5.6
	Summer	**Winter**	**p**
Environmental			
Day Length (hrs)	13.4 ± 1.4 [9.9-15.9]	7.7 ± 1.8 [4.9-11.3]	**<0.001**
Outdoor Temperature (^oC)	7.9 ± 2.7 [1.9 - 11.3]	2.3 ± 2.7 [-3.4 - 6.1]	**<0.001**
Daily Average White Light Exposure (Lux)	221.0 ± 189.5 [16.2 - 826.8]	82.3 ± 84.8 [2.5 - 514.2]	**<0.001**
Rest Time White Light Exposure (Lux)	27.8 ± 43.7 [0.2 - 210.5]	28.7 ± 55.6 [0.1 - 227.0]	0.91
Sleep Time White Light Exposure (Lux)	24.7 ± 43.3 [0.1 - 210.5]	26.5 ± 54.7 [0.0 - 222.3]	0.82
Activity Measures*			
Valid Days of Wear (>10hrs, n)	6.3 ± 0.9 [4.0 - 7.0]	6.4 ± 0.9 [4.0 - 7.0]	0.57
Wear-time (min)	815.2 ± 79.4 [681.3 - 1041.0]	802.7 ± 67.2 [663.3 - 1022.0]	0.06
TPA ($1000counts \times day^{-1}$)	103.8 ± 58.8 [17.9 - 349.7]	95.2 ± 59.8 [16.3 - 30.8]	**<0.05**
WT-PA ($counts \times min^{-1}$)	125.6 ± 69.0 [24.1 - 453.1]	117.8 ± 73.1 [22.2 - 401.5]	0.14
Sleep Measures			
Rest Duration (min)†	539.0 ± 72.0 [371.6 - 687.2]	554.8 ± 69.6 [330.9 - 689.0]	
Sleep Duration (min)	464.8 ± 78.9 [190.7 - 642.4]	473.8 ± 66.3 [301.8 - 635.3]	
Onset Latency (min)	39.5 ± 34.1 [4.4 - 208.2]	45.2 ± 34.6 [3.7 - 155.3]	
Sleep Efficiency (%)	80.4 ± 10.1 [36.5 - 91.8]	79.3 ± 8.5 [56.8 - 93.8]	
Waking after sleep onset (WASO) (min)	32.1 ± 15.5 [7.3 - 99.4]	35.7 ± 20.4 [9.3 - 116.6]	
Number of Awakenings (n)	45.5 ± 17.2 [13.0 - 104.0]	47.3 ± 8.4 [16.4 - 125.1]	
Bed Time (hh:mm ± min)	23:34 ± 68.7 [20:15 - 03:49]	23:39 ± 77.3 [20:52 - 05:16]	
Rise Time (hh:mm ± min)†	08:34 ± 67.9 [05:11 - 11:51]	08:55 ± 62.4 [06:08 - 10:47]	
Mid-Sleep Time (hh:mm ± min)†	04:44 ± 39.1 [03:12 - 07:17]	04:57± 37.8 [03:45 - 08:01]	

*N = 70 (25M, 45F) for Activity measures; †Sleep measures found to vary significantly with day length using linear mixed model analysis. Significant difference between seasons ($p<0.05$) is bolded.

Table 6: Descriptive statistics for participants (n=352) shown separately for women and men, for those above (GM high) and below the median for GM at baseline (GM low), and for those above (WM high) and below (low WM) the median for WM at baseline (Paper IV). Data are presented as mean (±SD).

Demographics	Men (n=137)	Women (n=215)	GM low (n=176)[a]	GM high (n=176)[a]	WM low (n=176)[a]	WM high (n=176)[a]
Age [a]	79.2 (4.0)	79.0 (4.6)	80.3 (4.6)	77.9 (3.7)	80.6 (4.5)	77.6 (3.7)
BMI (kg x m^{-2}) [a]	26.9 (3.8)	26.9 (4.7)	26.2 (4.2)	27.6 (4.4)	27.1 (4.4)	26.8 (4.3)
Weight (kg) [a]	83.9 (13.6)	70.9 (13.4)	75.4 (15.1)	76.5 (14.7)	76.2 (15.9)	75.6 (13.9)
ICV (cm^3) [b]	1617 (122)	1409 (96)	1544 (145)	1435 (129)	1489 (144)	1490 (151)
GM (%) [b, c]	45.1 (2.7)	47.3 (2.7)	44.3 (1.9)	48.7 (1.7)	46.0 (2.8)	47.0 (2.9)
WM (%) [b, c]	26.1 (1.6)	26.2 (1.7)	26.0 (1.7)	26.4 (1.6)	24.9 (1.1)	27.5 (0.89)
GM-5yr (%) [a, c]	43.9 (2.7)	46.7 (2.8)	43.4 (2.1)	47.9 (1.9)	45.0 (3.0)	46.2 (3.0)
WM-5yr (%) [a, c]	24.7 (1.9)	24.9 (1.9)	24.5 (1.9)	25.1 (1.8)	23.4 (1.4)	26.2 (1.1)
Δ-GM (%) [d]	-1.2 (1.1)	-0.65 (1.0)	-0.91 (1.2)	-0.85 (0.93)	-0.92 (1.2)	-0.83 (1.0)
Δ-WM (%) [d]	-1.3 (0.83)	-1.4 (0.67)	-1.5 (0.82)	-1.2 (0.62)	-1.4 (0.81)	-1.3 (0.65)
Wear-time (h:min x day^{-1}) [a]	13:59 (1:18)	13:47 (1:13)	13:45 (1:20)	13:58 (1:10)	13:46 (1:20)	13:57 (1:10)
SB (h:min x day^{-1}) [a]	10:31 (1:27)	10:06 (1:23)	10:20 (1:21)	10:11 (1:29)	10:30 (1:27)	10:01 (1:21)
TPA (1,000counts x day^{-1}) [a]	120 (68)	114 (61)	106 (56)	127 (69)	101 (57)	132 (67)
WT-PA (counts x min^{-1}) [a]	143 (81)	136 (70)	127 (65)	151 (81)	121 (67)	157 (77)

BMI= Body max index; ICV= intra-cranial volume; GM= gray matter, WM= white matter, PA= physical activity; SB= sedentary behavior;
TPA= Total PA (counts × day-1); WT-PA= wear-time adjusted PA (counts × min-1).
a= Follow-up (5-yr) measurements; b= Baseline measurements; c= Brain volumes as percent of ICV; d= 5-year change (follow-up – baseline).

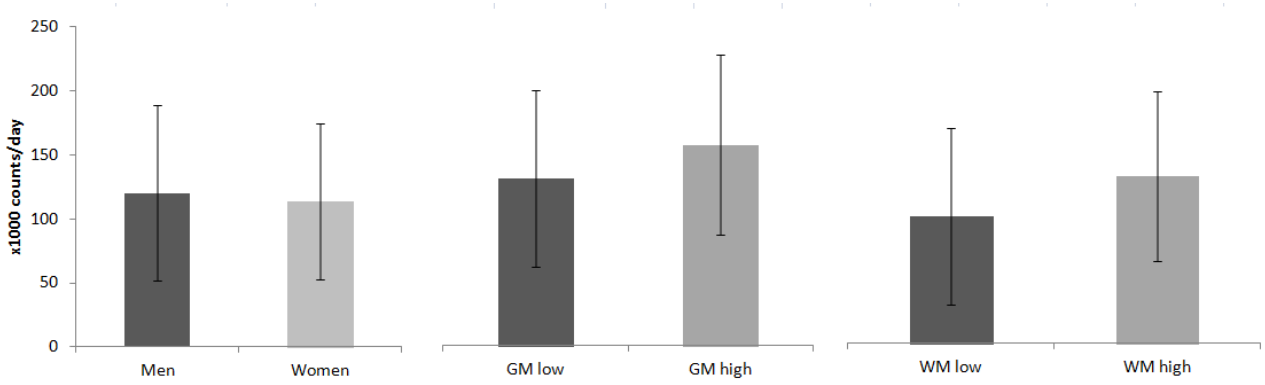

Figure 8: The mean (±SD) amount of total physical activity (TPA) for men and women, those with low gray matter (GM) and high GM, and those with low white matter (WM) and high WM (Paper IV).

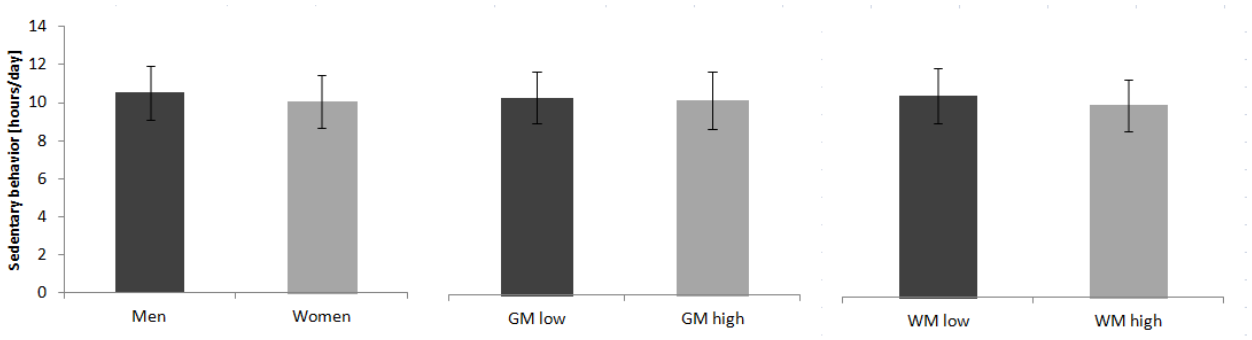

Figure 9: The mean (±SD) amount of sedentary behavior (SB) for men and women, those with low gray matter (GM) and high GM, and those with low white matter (WM) and high WM (Paper IV).

4.2 Main findings from Paper I

Physical Activity and Sedentary Behavior

Men had 18 min longer average daily wear-time than women (p= 0.024; see Table 2). While the average PA level during the valid days among participants varied widely (9,300–400,000 TPA; 15–491 WT-PA (counts × min^{-1})), men had slightly higher average PA than women (TPA: p= 0.048; WT-PA: p= 0.092). Sedentary time was the largest component of the total wear-time (74.5%), followed by LLPA (21.3%) and MVPA (1%) in the participants as a group. Women spent more time in LLPA and less in MVPA compared with men, but had less sedentary time compared with men (all p< 0.001). The average time spent in MVPA per week was 9.9 min × day^{-1} for men and 5.0 min × day^{-1} for women. The total time spent in any of the PA intensity levels (LLPA+HLPA+MVPA) is thus 202 min for men (3:22 h:min) and 214 min (3:34 h:min) for women. In both men and women, except for sedentary time, the PA variables TPA, WT-PA, LLPA, HLPA and MVPA decreased progressively with advancing age (Table 7).

BMI

Except for sedentary time, BMI was negatively related to all PA variables. Furthermore, multiple linear regression analysis, using BMI and age as continuous variables, showed that the association of BMI and the PA parameters was independent of age and gender (Table 8). The proportion of subjects having at least one bout of MVPA10+ during PA measurements also declined with an increasing BMI (Figure 10).

Daily changes in PA

Within an average day, the majority of the PA occurred during the hours between 8 a.m. and midnight (Figure 11). In all age groups, there was a significant (p< 0.001) sex difference in within-day PA variation. Post hoc analysis (Bonferroni) indicated that men were more physically active than women between both 4 a.m.– 8 a.m. and 8 a.m.– noon. Also, there was a significant difference in within-day PA variation and age groups (p< 0.001), which is explained by more decline in PA with increasing age during the day than during the night. Further examination showed the relative decline in PA with age to be very similar for all day hexiles, except for the midnight – 4 a.m. hexile that show relatively more decline in PA with age than the other day hexiles.

Day of week difference in PA

There was a significant difference in activity by day of the week when adjusted for difference between subjects (p< 0.001). Participants were significantly less active on Sundays (TPA 98 × 10^3 counts × day^{-1}) compared with other days of the week (114 × 10^3 counts × day^{-1}; Tukey HSD: p< 0.001). Saturdays also had less activity than Wednesdays and Thursdays. Age and gender distribution of valid accelerometer data was the same for all days of the week.

Bouts of PA

In the <75 years age group, 60% of men and 34% of women had at least one bout ≥10 min of MVPA (MVPA10+) during PA measurements (Figure 10). This proportion declined with age, and only 9% of the women and 25% of men in the >85-year age group had at least one bout of MVPA10+.

Swimming

About quarter of all participants reported swimming as an exercise, both during summer and winter, but of those who swim, only 25% swim for >30 min each time. Those who reported swimming as an exercise, also had more TPA and WT-PA (TPA: 121 × 10^3 counts × day^{-1} for swimmers vs. 91 × 10^3 counts × day^{-1} for non-swimmers; p< 0.001). Men used swimming more as an exercise compared with women, both during summer and winter (Chi-Square: p< 0.001). There was no age group difference in using swimming as an exercise during the winter (p= 0.069), but an age group difference was present during the summer (p= 0.013).

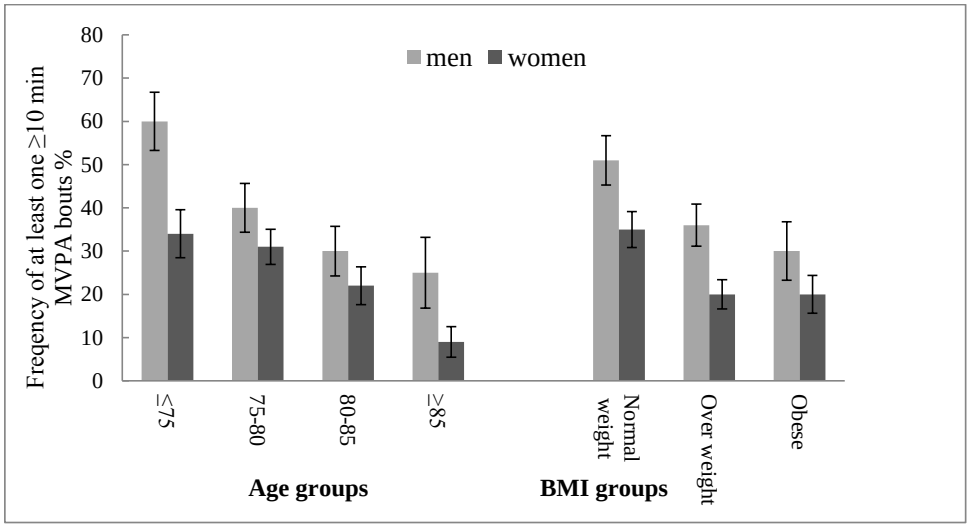

Figure 10: Proportion (SEp) of subjects with more than one MVPA10+ bouts by age groups and gender (n=579; men= 221, women=358; Paper I) and by BMI categories and gender (n=577; men=220, women=357).

Table 7: Descriptive statistics by age-groups for subjects with four or more days with 10 or more hours of wear-time used in Paper I. For cut-points see Troiano et al. [6] and Matthews et al. [9, 149].

Variables	Men		Women		Age
	n	Mean (SD)	n	Mean (SD)	p
Wear-time (min × day^{-1})					
Age groups ≤74.9	53	859 (96)	73	837 (78)	<0.001*
75-79.5	76	831 (91)	130	833 (90)	
80-84.9	64	818 (77)	90	802 (77)	
≥85	28	816 (109)	65	773 (65)	
TPA (1000counts × day^{-1})					
Age groups ≤74.9	53	146 (67)	73	130 (71)	<0.001*
75-79.5	76	125 (67)	130	116 (55)	
80-84.9	64	95 (61)	90	94 (45)	
≥85	28	89 (60)	65	72 (41)	
WT-PA (count × min^{-1})					
Age groups ≤74.9	53	171 (77)	73	154 (80)	<0.001*
75-79.5	76	150 (78)	130	139 (62)	
80-84.9	64	115 (69)	90	116 (51)	
≥85	28	106 (67)	65	92 (52)	
SB (hours × day^{-1}) [a]					
Age groups ≤74.9	53	10.5 (1.8)	73	9.9 (1.4)	0.15
75-79.5	76	10.3 (1.5)	130	10.0 (1.5)	
80-84.9	64	10.7 (1.3)	90	10.0 (1.3)	
≥85	28	10.7 (1.7)	65	10.2 (1.1)	
SB% (percent × weartime^{-1})					
Age groups ≤74.9	53	73.5% (8.8%)	73	71.5% (9.2%)	<0.001*
75-79.5	76	74.3% (7.8%)	130	72.1% (7.7%)	
80-84.9	64	78.2% (7.4%)	90	75.0% (8.2%)	
≥85	28	79.0% (8.2%)	65	78.9% (7.9%)	
LLPA (min × day^{-1})					
Age groups ≤74.9	53	178 (63)	73	197 (64)	<0.001*
75-79.5	76	169 (50)	130	198 (53)	
80-84.9	64	150 (51)	90	175 (59)	
≥85	28	148 (56)	65	145 (55)	
HLPA (min × day^{-1})					
Age groups ≤74.9	53	35 (22)	73	36 (28)	<0.001*
75-79.5	76	34 (25)	130	30 (23)	
80-84.9	64	21 (18)	90	24 (16)	
≥85	28	19 (16)	65	17 (18)	
MVPA (min × day^{-1})					
Age groups ≤74.9	53	14.5 (15.0)	73	7.6 (9.6)	<0.001*
75-79.5	76	10.0 (11.7)	130	5.6 (7.5)	
80-84.9	64	7.4 (12.6)	90	3.7 (5.1)	
≥85	28	6.8 (10.3)	65	2.3 (4.0)	

PA= Physical activity; TPA= Total PA (counts × day^{-1}); WT-PA= wear-time adjusted PA (counts × min^{-1}); SB= Sedentary behavior (0-99 counts × min^{-}1); SB%= SB adjusted for wear-time; LLPA= Low-light PA (100-759 counts × min^{-1}); HLPA= High-light PA (760-2019 counts × min^{-1}); MVPA= Moderate-to-vigorous PA (≥2020 counts × min^{-1}). *Significant correlation with age, adjusted for BMI and gender (multiple linear regression).

Table 8: Descriptive statistics by BMI-groups for subjects with four or more days with 10 or more hours of wear-time in Paper I. For cut-points see Troiano et al. [6] and Matthews et al. [9, 149].

Variables		Men		Women		BMI
		n	Mean (SD)	n	Mean (SD)	p
Wear-time (min × day^{-1})						
BMI groups [a]	Normal weight	77	835 (102)	132	816 (75)	0.17
	Overweight	97	823 (82)	141	814 (88)	
	Obese	46	843 (95)	84	816 (89)	
TPA (1000counts × day^{-1})						
BMI groups [a]	Normal weight	77	128 (78)	132	113 (61)	<0.001*
	Overweight	97	114 (64)	141	103 (56)	
	Obese	46	106 (56)	84	97 (53)	
WT-PA (count × min^{-1})						
BMI groups [a]	Normal weight	77	152 (89)	132	137 (69)	<0.001*
	Overweight	97	137 (74)	141	125 (63)	
	Obese	46	125 (63)	84	119 (62)	
SB (hours × day^{-1})						
BMI group [a]	Normal weight	77	10.5 (1.6)	132	9.9 (1.2)	0.13
	Overweight	97	10.3 (1.4)	141	10.0 (1.4)	
	Obese	46	10.7 (1.5)	84	10.3 (1.5)	
SB% (percent × weartime^{-1})						
BMI groups [a]	Normal weight	77	75.8% (8.2%)	132	72.9% (8.7%)	0.002*
	Overweight	97	75.5% (8.6%)	141	73.8% (8.8%)	
	Obese	46	76.7% (7.7%)	84	75.5% (8.0%)	
LLPA (min × day^{-1}) [b]						
BMI groups [a]	Normal weight	77	161 (56)	132	189 (62)	0.012*
	Overweight	97	165 (56)	141	184 (61)	
	Obese	46	163 (54)	84	171 (54)	
HLPA (min × day^{-1}) [c]						
BMI groups [a]	Normal weight	77	28 (19)	132	28 (23)	0.028*
	Overweight	97	30 (25)	141	27 (24)	
	Obese	46	29 (22)	84	25 (22)	
MVPA (min × day^{-1})						
BMI groups [a]	Normal weight	77	13.9 (17.2)	132	6.3 (8.1)	<0.001*
	Overweight	97	8.4 (9.5)	141	4.1 (5.6)	
	Obese	46	6.6 (8.6)	84	4.3 (7.7)	

BMI= Body max index; PA= Physical activity; TPA= Total PA (counts × day^{-1}); WT-PA= wear-time adjusted PA (counts × min^{-1}).; SB= Sedentary behavior (0-99 counts × min^{-}1); SB%= SB adjusted for wear-time; LLPA= Low-light PA (100-759 counts × min^{-1}); HLPA= High-light PA (760-2019 counts × min^{-1}). MVPA= Moderate-to-vigorous PA (≥2020 counts × min^{-1}).
a= Normal weight BMI< 25kg×m^{-2}, overweight BMI= 25-29.9 kg×m^{-2}, obese BMI≥30 kg×m^{-2}.
*Significant correlation with BMI, adjusted for age and gender (multiple linear regression).

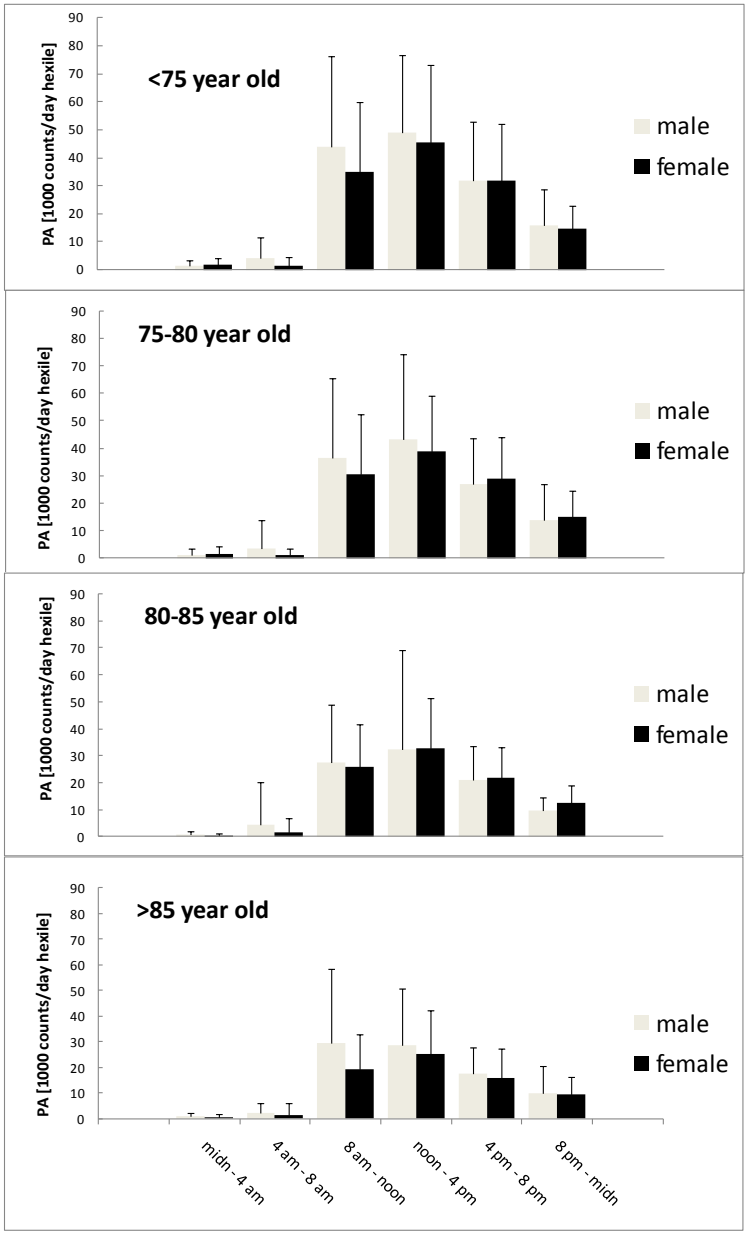

Figure 11: Distribution of PA between day hexiles (4 hour periods) for different age groups and sexes (Paper I). Beside a significant difference in PA between different day hexiles ($p<0.001$), ANOVA for repeated measures (on square root transformed data) showed significant interactions of the within-day distribution of PA with both gender ($p<0.001$) and age groups ($p<0.001$); 3-way interactions were non-significant ($p=0.65$).

4.3 Main findings from Paper II

Environmental measures

Average day length and temperature during activity measurements, as well as selected activity variables for the longitudinal design are shown in Table 3. During the summer, which had more daylight and higher temperature, more time was spent in all PA categories except for MVPA (and WT-MVPA) and less time was spent in SB.

Predictors of Physical Activity

On days with higher temperature (or longer daylight), there were higher values for all PA variables except for the MVPA (and WT-MVPA). Lower temperature was associated with more SB over both seasons (standardized β value, β= -0.16). Results of the mixed model ANOVA are shown in Table 9. Due to high colinearity between the seasonal variables (day length or temperature) separate models were calculated for each time. Inclusion of either seasonal variable in the models, caused differences between summer and winter in any of the PA and SB variables to become non-significant (statistical results not shown). When the day length variable was replaced by the temperature variable, the results were very similar. Age was most strongly associated with all PA variables and with the day-to-day variation in the same variables, with β values from -0.25 to -0.44. More SB was also most strongly associated with older age (β= 0.36). There was an inverse association between BMI and all PA variables, with β values from -0.16 to -0.24, and a direct association was between SB and BMI (β= 0.18). Women had more LLPA (β= 0.16) (and WT-LLPA β= 0.16) compared to men. Self-reported health status was not associated with any of the PA variables. Analyzing the cross-sectional data for the whole sample (590 subjects) using regression analysis revealed same effects of seasonal variables (very similar betas, CI and p-values) as for the longitudinal data presented here (data not shown).

Bouts of Physical Activity

Most of the high active participants achieved at least one ≥5 minutes bout of LSPA over all valid days, both during summer and winter, but only 58% the low active participants achieved at least one ≥5 minutes bout of LSPA over all valid days during the winter and around 78% during the summer (Table 10). The number of bouts, counts and minutes accumulated in ≥5 minutes bouts of LSPA were higher during the summer compared with winter in both low- and high active participants and there was a significant difference between the low- and high active participants. Difference between summer and winter in all above variables was significantly higher for high activity participants than for low activity participants, i.e. significant interaction (Table 10). Half of the high active participants achieved at least one ≥10 minutes bout of MVPA over all valid days, both during summer and winter, and less then 10% of the low active participants achieved at least one ≥10 minutes bout of MVPA over all valid days during both seasons (Table 11). The low active participants did not accumulate any number of bouts, counts and minutes in ≥10 minutes bouts of MVPA, while those classified as high active accumulated significantly higher values for all variables (Table 11).

Table 9: Results of the mixed model ANOVA analysis of PA and SB parameters for subjects with repeated visits in the AGESII cohort (Paper II). Covariates included age, sex, BMI, self-reported health status, day length and temperature. Data are presented as standardized β (β), 95% confidence level (95% CL) and p-value. A negative β value indicates an inverse relationship. Significant relationships (p<0.05) are bolded. Two separate models were run for each variable, where only one seasonal variable (temperature or day length) was in each model; seasonal variables with higher β are marked with †. Other variables were included in both models but are shown in the table only for the model with the higher β of the seasonal variables.

Variables		Temperature/Day length			Age			Female			BMI			Health status		
		β	**95%CL**	**p**	**β**	**95%CL**	**p**	**β**	**95%CL**	**p**	**β**	**95%CL**	**p**	**β**	**95%CL**	**p**
WT-SB	Temperature	**-0.16†**	**-0.21;-0.10†**	**<0.0001†**	**0.36**	**0.21;0.50**	**<0.0001**	-0.12	-0.27;0.02	0.10	**0.18**	**0.03;0.33**	**0.02**	0.07	-0.08;0.22	0.35
	Day length	**-0.16**	**-0.21;-0.11**	**<0.0001**												
SD-WT-SB	Temperature	**0.13**	**0.04;0.22**	**0.007**												
	Day length	**0.18†**	**0.09;0.27†**	**0.0001†**	**-0.30**	**-0.43;-0.16**	**<0.0001**	-0.01	-0.15;0.12	0.85	-0.10	-0.24;0.04	0.14	-0.04	-0.18;0.09	0.53
TPA[a]	Temperature	**0.17†**	**0.11;0.22†**	**<0.0001†**	**-0.44**	**-0.58;-0.29**	**<0.0001**	-0.04	-0.18;0.10	0.60	**-0.21**	**-0.35;-0.06**	**0.005**	-0.11	-0.25;-0.03	0.13
	Day length	**0.14**	**0.09;0.19**	**<0.0001**												
WT-TPA[a]	Temperature	**0.15†**	**0.10;0.20†**	**<0.0001†**	**-0.42**	**-0.56;-0.28**	**<0.0001**	-0.02	-0.17;0.12	0.73	**-0.21**	**-0.35;-0.06**	**0.005**	-0.12	-0.26;0.03	0.11
	Day length	**0.13**	**0.07;0.18**	**<0.0001**												
SD-TPA[a]	Temperature	**0.13**	**0.05;0.20**	**0.0007**												
	Day length	**0.15†**	**0.08;0.21†**	**<0.0001†**	**-0.39**	**-0.53;-0.25**	**<0.0001**	-0.11	-0.25;0.02	0.10	**-0.21**	**-0.35;-0.07**	**0.004**	-0.10	-0.24;0.04	0.14
LLPA[a]	Temperature	**0.14**	**0.08;0.19**	**<0.0001**												
	Day length	**0.15†**	**0.10;0.21†**	**<0.0001†**	**-0.32**	**-0.47;-0.17**	**<0.0001**	**0.16**	**0.01;0.30**	**0.04**	**-0.16**	**-0.31;-0.01**	**0.04**	-0.01	-0.17;0.14	0.85
WT-LLPA[a]	Temperature	**0.11**	**0.06;0.17**	**0.0001**												
	Day length	**0.14†**	**0.08;0.19†**	**<0.0001†**	**-0.29**	**-0.44;-0.14**	**0.0002**	**0.19**	**0.04;0.34**	**0.01**	**-0.16**	**-0.31;-0.01**	**0.04**	-0.02	-0.17;0.13	0.78
SD-LLPA[a]	Temperature	0.07	-0.03;0.17	0.18												
	Day length	**0.13†**	**0.04;0.23†**	**0.007†**	**-0.25**	**-0.39;-0.12**	**0.0003**	0.04	-0.09;0.17	0.54	-0.08	-0.22;0.05	0.23	-0.001	-0.14;0.14	0.99
LSPA[a]	Temperature	**0.18†**	**0.12;0.24†**	**<0.0001†**	**-0.43**	**-0.57;-0.29**	**<0.0001**	-0.06	-0.20;0.08	0.39	**-0.17**	**-0.31;-0.02**	**0.022**	-0.13	-0.27;-0.01	0.07
	Day length	**0.15**	**0.10;0.21**	**<0.0001**												
WT-LSPA[a]	Temperature	**0.17†**	**0.11;0.23†**	**<0.0001†**	**-0.42**	**-0.56;-0.28**	**<0.0001**	-0.05	-0.19;0.09	0.47	**-0.16**	**-0.31;-0.02**	**0.025**	-0.14	-0.28;-0.01	0.06
	Day length	**0.14**	**0.08;0.20**	**<0.0001**												
SD-LSPA[a]	Temperature	**0.19†**	**0.11;0.26†**	**<0.0001†**	**-0.37**	**-0.50;-0.23**	**<0.0001**	-0.08	-0.22;0.06	0.24	**-0.19**	**-0.33;-0.05**	**0.008**	-0.13	-0.27;-0.01	0.06
	Day length	**0.18**	**0.11;0.25**	**<0.0001**												
MVPA[a]	Temperature	**0.08†**	**0.01;0.14†**	**0.027†**	**-0.33**	**-0.47;-0.19**	**<0.0001**	-0.13	-0.27;0.01	0.07	**-0.24**	**-0.39;-0.10**	**0.001**	-0.11	-0.26;0.03	0.12
	Day length	0.05	-0.02;0.11	0.151												
WT-MVPA[a]	Temperature	**0.07†**	**0.001;0.14†**	**0.048†**	**-0.32**	**-0.46;-0.18**	**<0.0001**	-0.13	-0.27;0.01	0.08	**-0.24**	**-0.39;-0.10**	**0.001**	-0.11	-0.26;-0.03	0.12
	Day length	0.04	-0.03;0.10	0.257												
SD-MVPA[a]	Temperature	**0.09†**	**0.01;0.17†**	**0.028†**	**-0.31**	**-0.45;-0.18**	**<0.0001**	-0.11	-0.25;0.02	0.10	**-0.24**	**-0.38;-0.10**	**0.001**	-0.09	-0.23;0.05	0.21
	Day length	**0.08**	**0.002;0.15**	**0.045**												

PA= Physical activity; WT-… = Physical activity variables normalized for wear time; SD= Standard deviation, day to day variation in each PA/SB variable; SB= Sedentary behavior; TPA=Total PA; LLPA=Low-light PA (100-759 counts × min^{-1}); LSPA= Lifestyle PA (≥760 counts × min^{-1}); MVPA=Moderate-to-vigorous PA (≥2020 counts × min^{-1}); *a*= Square root transformed; **†** = seasonal variable with higher β.

Table 10: Median value (MD) and inter quartile limits (IQL) for the mean values of valid days, for ≥5 min bouts of LSPA for sub-population of participants with repeat visits during summer and winter, presented separately for low- and high active participants. Low vs. high active participants were separated by the median of average TPA for summer and winter. Also, the proportion of participants who reached any bout of ≥5 min of LSPA.

	Low active (n=69)		**High active (n=69)**		**p**	**p**	**p**
	Winter	**Summer**	**Winter**	**Summer**	**Season**	**Low/High**	**Interaction**
Number of participants who achieved at least one bout of LSPA ≥5 min	40 (58.0%)	54 (78.4%)	69 (100%)	68 (98.6%)	**0.012** [a]	**<0.0001** [d]	**0.002** [e]
All subjects with repeated measures during summer and winter	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**			
Number of ≥5 min bouts of LSPA [day^{-1}]	0.17 (0; 0.50)	0.33 (0.14; 0.86)	1.5 (1.0; 2.43)	2.43 (1.29; 3.71)	**<0.0001** [b]	**<0.0001** [c]	**0.001** [e]
Counts accumulated in ≥5min bouts of LSPA [counts × day^{-1}]	1,033 (0; 4,238)	3,600 (867; 8,136)	18,608 (9,135; 55,740)	31,952 (17,574 ; 70,021)	**0.0005** [b]	**<0.0001** [c]	**0.035** [e]
Minutes accumulated in ≥5 min bouts of LSPA [min:s × day^{-1}]	0:50 (0; 3:26)	2:40 (0:50; 5:43)	12:43 (7:10; 26:08)	22:17 (10:06; 35:40)	**<0.0001** [b]	**<0.0001** [c]	**0.008** [e]

LSPA= Lifestyle PA (≥760 counts × min^{-1}); MD= Median value; IQL= Inter quartile limits; *a* = McNemar´s test used to compare summer and winter; *b*= Wilcoxon Singed Rank test used to compare winter and summer; *c*= Wilcoxon test, low- and high active compared; *d*= Chi-Square test, low- and high active compared; *e*= Wilcoxon test of summer to winter change between low vs. high active participants (season-TPA interaction). Significant relationship (p<0.05) is bolded.

Table 11: Median value (MD) and inter quartile limits (IQL) for the mean values of valid days, for ≥10 min bouts of MVPA for sub-population of participants with repeat visits during summer and winter, presented separately for low- and high active participants. Low vs. high active participants were separated by the median of average TPA for summer and winter. Also, the proportion of participants who reached any bout of ≥10 min of MVPA.

	Low active (n=69)		**High active (n=69)**		**p**	**p**	**p**
	Winter	**Summer**	**Winter**	**Summer**	**Season**	**Low/High**	**Interaction**
Number of participants that achieved at least one bout of MVPA ≥10 min	6 (8.7%)	6 (8.7%)	34 (49.3%)	35 (50.1%)	0.85 [a]	**<0.0001** [d]	0.84 [e]
All subjects with repeated measures during summer and winter	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**			
Number of ≥10 min bouts of MVPA [day^{-1}]	0 (0; 0)	0 (0; 0)	0 (0; 0.43)	0.14 (0;0.33)	0.85 [b]	**<0.0001** [c]	0.48 [e]
Counts accumulated in ≥10min bouts of MVPA [counts ×day^{-1}]	0 (0; 0)	0 (0; 0)	0 (0; 19,690)	3,377 (0; 14,105)	0.29 [b]	**<0.0001** [c]	0.78 [e]
Minutes accumulated in ≥10min bouts of MVPA [min:s × day^{-1}]	0 (0; 0)	0 (0; 0)	0 (0; 6:30)	1:34 (0; 4:30)	0.33 [b]	**<0.0001** [c]	0.59 [e]

MVPA= Moderate-to-vigorous PA (≥2020 counts × min^{-1}); MD= Median value; IQL= Inter quartile limits; *a* = McNemar´s test used to compare summer and winter; *b*= Wilcoxon Singed Rank test used to compare winter and summer; *c*= Wilcoxon test, low- and high active compared; *d*= Chi-Square test, low- and high active compared; *e*= Wilcoxon test of summer to winter change between low vs. high active participants (season-TPA interaction). Significant relationship (p<0.05) is bolded.

4.4 Main findings from Paper III

Cross sectional results

Sleep and Environmental Factors

The daily hours of daylight over the study period varied widely, from 4.4 hours (December) to 16 hours (August) and the average outdoor temperature varied from -3.1^{o}C to 11.3^{o}C. Patterns of sleep are presented in Table 4. Both men and women went to bed at around the same time (23:28 ± 61.9 min), but men arose earlier (08:15 ± 69.5 min vs. 08:51 ± 54.6 min, $p<0.01$) leading to significantly shorter rest (529.4 ± 72.4 vs. 557.6 ± 60.4 min × night^{-1}, $p<0.01$) and sleep durations (461.7 ± 79.9 vs. 486.9 ± 68.0 min × night^{-1}, $p<0.01$). Men awoke more often during sleep than women (46.5 ± 18.3 vs. 40.2 ± 15.7 awakenings × night^{-1}, $p<0.01$). There were no gender differences in sleep efficiency, WASO, or onset latency.

Physical Activity

Cross-sectional PA data is presented in Table 4 Most subjects (>85%) acquired 6 or more valid days of PA measurement. There were no significant differences between men and women in terms of valid days of wear, daily wear-time, daily activity counts, or counts per wear-time minute.

Predictors of sleep measures

The results of the backward-elimination multiple regression analyses are presented in Table 12. Both increases in age and in BMI were independently associated with a decrease in sleep efficiency and an increase in WASO. Age was also negatively associated with both bed time and rise time, suggesting that, as age advances, individuals go to bed and rise earlier. The multiple regression analysis also confirmed the independent association between genders and rest and sleep duration, with men having shorter durations as a result of earlier rise times compared to women. The analysis also confirmed that men had a greater number of awakenings during the night. Sleep medication usage was found to independently predict longer rest duration and onset latency and later rise and mid-sleep times, while diagnosed depression was found to significantly predict longer sleep duration and shorter onset latency. Higher daily PA was only found to be independently associated with earlier rise times. Interestingly, length of daylight was also found to independently predict rest and sleep duration and mid-sleep and rise times. On days with greater number of daylight hours, participants tended to have significantly shorter rest durations (β=-5.2 min × daylight hour^{-1}) and sleep durations (β=-4.1 min × daylight hour^{-1}) and earlier rise times (β=-3.5 min × daylight hour^{-1}) and mid-sleep times (β=-1.9 min × daylight hour^{-1}). Additionally, models pertaining to sleep timing and duration, including the mid-sleep and rise times and rest and sleep durations, had the highest adjusted R^2 values and included both day length and gender as significant independent predictors. Neither self-reported health status nor average outdoor temperature was found to independently predict any of the sleep outcomes.

Repeated measures in a subgroup

Environmental Measures

Sleep watch light sensor data indicated that participants were exposed to a greater daily amount of white light during periods of longer day length compared to those with shorter day length (221.0 ± 189.5 vs. 82.3 ± 84.8 lux, respectively, $p<0.001$), see Table 5. However, there were no differences in the white light exposure recorded by the Actiwatches during rest or sleep time between the two measurement periods.

Physical Activity

When days were longer, participants had higher TPA counts (103,781 ± 58,777 vs. 95,152 ± 59,786 counts, $p<0.05$) but also trended toward longer device wear-times (815.2 ± 79.4 vs. 802.7 ± 67.2 min, $p= 0.06$), see Table 5. Consequently, there was no difference between periods of longer and shorter day lengths when PA was normalized for wear-time (125.6 ± 69.0 vs. 117.8 ± 73.1 counts × wear-time min^{-1}, respectively, $p= 0.14$).

Sleep

Results of the linear mixed effects model performed on the repeat subpopulation are summarized in Table 13. After controlling for demographic variables and environmental conditions in the linear mixed model, participants with repeat visits tended to rise earlier in summer months (β=-3.8 min × daylight $hour^{-1}$, $p<0.01$) but go to bed at approximately the same time ($p>0.05$), leading to a shift toward earlier mid-sleep times (β=-2.2 min × daylight $hour^{-1}$, $p<0.01$) and a reduced rest duration (β=-3.4 min × daylight $hour^{-1}$, $p<0.05$). Sleep duration, sleep efficiency, sleep onset latency, WASO, and number of awakes were not found to vary significantly with hours of day light. Similar to the cross-sectional results, gender also had a significant, independent influence on sleep with women having longer onset latency (β=16.7 min, $p<0.05$) and later rise (β=46.3 min, $p<0.01$) and mid-sleep times (β=18.9 min, $p<0.05$) than men. Participants who used sleep medications were found to have a significantly longer rest duration (β=38.8 min, $p<0.05$) and later mid-sleep time (β=23.1 min, $p<0.05$). PA was also found to have a small, but significant impact onset latency (β=0.11 min × wear-time $count^{-1}$, $p<0.05$) and bed time (β=-0.18 min × wear-time $count^{-1}$, $p<0.05$). None of the other covariates such as age, BMI, health status, and diagnosed depression, were found to influence sleep patterns or quality in the repeat subpopulation. Outdoor temperature was excluded as a covariate due to co-linearity with day length; however results did not change appreciably when it was included.

Table 12: Results of backward-elimination, multiple regression analysis of cross-sectional sleep parameters for AGES II cohort (Paper III). Separate models were used to evaluate each sleep parameter. Covariates included BMI, self-reported health status, gender, age, outdoor temperature, day length, sleep medication usage, diagnosed depression, and WT-PA. Data are presented as standardized Beta (p-value). A negative standardized Beta value indicates an inverse relationship.

		Covariates †													
Sleep parameters *	**Adj. R^2**	**Day length**		**BMI**		**Women**		**Age**		**Activity**		**Sleep meds**		**Depression**	
		Std. β	(p)	Std. β	(p)	Std. β	(p)	Std. β	(p)	Std. β	(p)	Std. β	(p)	Std. β	(p)
Rest Duration	0.147	-0.24	(<0.01)	-	-	0.17	(<0.01)	-	-	-	-	0.23	(<0.01)	-	-
Sleep Duration	0.070	-0.17	(<0.01)	-	-	0.18	(<0.01)	-	-	-	-	-	-	0.13	(0.04)
Onset Latency	0.042	-0.12	(0.06)	-	-	-	-	-	-	-	-	0.18	(<0.01)	-0.14	(0.03)
Sleep Efficiency	0.021	-	-	-0.14	(0.04)	-	-	-0.14	(0.04)	-	-	-	-	-	-
WASO	0.047	-	-	0.19	(<0.01)	-	-	0.18	(<0.01)	-	-	-	-	-	-
Number of Awakenings	0.027	-	-	-	-	-0.18	(0.03)	-	-	-	-	-	-	-	-
Bed Time	0.024	-	-	-	-	-	-	-0.17	(<0.01)	-	-	-	-	-	-
Mid-Sleep Time	0.139	-0.17	(<0.01)	-	-	0.24	(<0.01)	-	-	-	-	0.21	(<0.01)	-	-
Rise Time	0.136	-0.17	(<0.01)	-	-	0.25	(<0.01)	-0.13	(0.04)	-0.14	(0.02)	-	-	0.11	(0.08)

WASO= Waking after sleep onset ; BMI= Body max index (kg × $hight^2$); ***** All models were adequately fit ($p<0.05$).
† Outdoor temperature and health status were not significant independent predictors of any sleep parameters tested and are not shown in the table.

Table 13: Results of a linear mixed models regression analysis of sleep parameters for the sub-population of participants with repeat visits during periods of longer and shorter day length (Paper III). Separate models were used to evaluate each sleep parameter. Fixed effects covariates included BMI, self-reported health status, gender, age, day length, sleep medication usage, diagnosed depression, and WT-PA. The subject identifier was used as the random effects variable. Data are presented as Beta, Standard Error (SE) and p-value for significant fixed effects covariates. A negative Beta value indicates an inverse relationship; significant relationships (p<0.05) are bolded.

	Fixed Effects Covariates [†]											
Sleep Parameters*	**Day Length**			**Women**			**Activity**			**Sleep Meds**		
	β	SE	p	β	SE	p	β	SE	p	B	SE	p
Rest Duration	**-3.37**	**1.10**	**(<0.01)**	14.92	16.05	(0.36)	0.15	0.10	(0.14)	**38.77**	**16.36**	**(0.02)**
Onset Latency	-1.25	0.66	(0.06)	**16.71**	**7.70**	**(0.03)**	**0.11**	**0.05**	**(0.04)**	5.82	7.88	(0.46)
Bed Time	-0.38	0.73	(0.61)	30.69	18.50	(0.10)	**-0.18**	**0.09**	**(0.04)**	-18.35	18.66	(0.33)
Mid-Sleep Time	**-2.22**	**0.48**	**(<0.01)**	**18.94**	**8.75**	**(0.03)**	0.04	0.05	(0.38)	**23.09**	**8.88**	**(0.01)**
Rise Time	**-3.79**	**0.84**	**(<0.01)**	**46.29**	**14.95**	**(<0.01)**	0.004	0.09	(0.96)	21.28	15.18	(0.17)

***** Results for sleep parameters with no significant predictors (sleep duration, sleep efficiency, number of awakenings, and wake after sleep onset (WASO)) are not presented. [†] Body Mass Index (BMI), health status, age, and diagnosed depression status were not significant independent predictors of any sleep parameters tested and are not shown in the table. Outdoor temperature was excluded as a covariate due to co-linearity with day length; however results did not change appreciably when it was included.

4.5 Main findings from Paper IV

PA, SB and brain volumes

Participants with lower GM averaged 106,000 counts × day^{-1} in TPA, but those with higher GM averaged 127,000 counts × day^{-1} in TPA. Participants with lower WM averaged 101,000 counts × day^{-1} in TPA, but those with higher WM averaged 132,000 in counts × day^{-1} in TPA (see Table 6 and Figure 8). For SB, those with lower GM spent 10:20 hours:min × day^{-1} sedentary, but those with higher GM spent 10:11 hours:min × day^{-1} sedentary. Participants with lower WM spent 10:30 hours:min × day^{-1}, but those with higher WM spent 10:01 hours:min × day^{-1} in SB (see Table 6 and Figure 9).

Regression Analysis of Physical Activity and Brain Volume

Results from linear regression models for TPA are shown in Table 14. With adjustments for age and sex (Models 1), all brain measurement variables were separately and significantly positively associated with TPA (all $p<0.05$), except the 5-year change in WM. Adding brain infarcts, days between baseline and follow-up measurements, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education as covariates (Model 2), did not change the significance or direction of the correlations, with the exception of the 5-year change in WM, which was found to have a significant, positive correlation with TPA ($p<0.05$). When both baseline brain volume and the 5-year brain volume change were included in the same model (Model 3), which also adjusted for the above potential confounding variables, all brain volumes were significantly associated with TPA (all $p<0.05$). Less brain volume at baseline and more 5-year loss, predict less PA.

Regression Analysis of Sedentary Behavior and Brain Volume

Results from linear regression models for SB are shown in Table 15. For SB, only WM at follow-up ($\beta= -0.092$; $p= 0.0032$) and the 5-year change in WM ($\beta= -0.080$; $p= 0.0051$) were separately associated, negatively, with SB. Less WM at follow-up and more 5-year decrease, predict more SB. When adjusting the models for the above covariates, lifestyle PA and wear-time, the same brain parameters were significantly negatively associated with SB (WM at follow-up: $\beta= -0.084$; $p= 0.012$); (5-year change in WM: $\beta= -0.10$; $p= 0.0010$). These associations remained in Model 3.

Table 14: Association between brain atrophy measures and total objectively measured physical activity (Paper IV). Brain volume measurements are presented as a percent of intra-cranial volume.

	Variables	Total Physical Activity (counts x day^{-1})			
		Std. β	Lower 95%CL	Upper 95%CL	p
Model 1[#]	GM [a]	0.16	0.047	0.27	0.0056
	WM [a]	0.20	0.093	0.31	0.00030
	GM-5yr [b]	0.24	0.12	0.35	<0.0001
	WM-5yr [b]	0.22	0.11	0.33	<0.0001
	Δ-GM [c]	0.17	0.063	0.27	0.0016
	Δ-WM [c]	0.090	-0.011	0.19	0.080
Model 2[# #]	GM [a]	0.12	0.012	0.23	0.029
	WM [a]	0.13	0.031	0.23	0.010
	GM-5yr [b]	0.17	0.063	0.28	0.0021
	WM-5yr [b]	0.16	0.062	0.26	0.0016
	Δ-GM [c]	0.11	0.015	0.21	0.024
	Δ-WM [c]	0.11	0.0095	0.20	0.032
Model 3[# # #]	GM [a]	0.11	0.0028	0.22	0.044
	WM [a]	0.11	0.011	0.21	0.030
	Δ-GM [c]	0.14	0.047	0.24	0.0037
	Δ-WM [c]	0.11	0.010	0.21	0.030

GM = gray matter, WM = white matter.
# Model 1 = Each variable entered separately and adjusted for age and sex.
Model 2 = Model 1 and additional adjustment for brain infarcts, days between baseline and follow-up measurements, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education.
Model 3 = Baseline and the 5-year change brain measurement variables (Δ) included in the same model with same adjustments as in model 2.
a = baseline measurement.
b = 5-yr follow-up measurement.
c = 5-year change (follow-up – baseline) (Δ).

Table 15: Association between brain atrophy measures and objective sedentary behavior (Paper IV). Brain volume measurements are presented as a percent of intra-cranial volume.

	Variables	Sedentary Behavior (hours x day^{-1})			
		Std. β	Lower 95%CL	Upper 95%CL	p
Model 1[#]	GM [a]	-0.011	-0.075	0.054	0.74
	WM [a]	-0.061	-0.12	0.00082	0.053
	GM-5yr[b]	-0.023	-0.091	0.044	0.49
	WM-5yr[b]	-0.092	-0.15	-0.031	0.0032
	Δ-GM [c]	-0.026	-0.085	0.033	0.38
	Δ-WM [c]	-0.080	-0.14	-0.024	0.0051
Model 2[# #]	GM [a]	-0.0042	-0.074	0.065	0.91
	WM [a]	-0.043	-0.11	0.022	0.19
	GM-5yr [b]	-0.011	-0.083	0.061	0.76
	WM-5yr [b]	-0.084	-0.15	-0.019	0.012
	Δ-GM [c]	-0.015	-0.077	0.047	0.64
	Δ-WM [c]	-0.10	-0.17	-0.042	0.0010
Model 3[# # #]	GM [a]	0.015	-0.056	0.085	0.68
	WM [a]	-0.037	-0.10	0.028	0.26
	Δ-GM [c]	-0.034	-0.10	0.029	0.28
	Δ-WM [c]	-0.11	-0.17	-0.047	0.0007

GM = gray matter, WM = white matter.
# Model 1= Each variable entered separately and adjusted for age, sex, wear-time and lifestyle PA.
Model 2 = Model 1 and additional adjustment for brain infarcts, days between baseline and follow-up measurements, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education.
Model 3 = Baseline and the 5-year change brain measurement variables (Δ) included in the same model with same adjustments as in model 2.
a = baseline measurement.
b = 5-year follow-up measurement.
c = 5-year change (follow-up – baseline) (Δ).

5 Discussion

The main findings of the four papers are that the Icelandic older population spends majority of their non-sleep time in SB. This trend increases with age, while the PA decreases. The total time spent in PA of all intensities was only 3.5 hours for both men and women. Despite large difference in daylight between seasons, relatively small, but significant, seasonal difference was found in PA and SB. The participants rose earlier in summer months, leading to reduced rest duration. PA had small, but significant impact on onset latency and bed time. The results also showed that less brain volume at baseline and more 5-year loss in brain volume, predict less PA, and more SB, even after adjustment for self-reported PA at baseline.

Physical Activity and Sedentary Behavior

It was surprising to find that the subjects spent very little time in MVPA (less than 10 minutes per day), and only about 21% of their accelerometer wear-time (assuming to be non-sleeping time) in LLPA, and about 75% of their time as sedentary. Since the subjects were considerably older than most other previously reported studies using accelerometers, it can be speculated that this could be a reason to explain the low PA levels in our cohort. The observation that all types of PA decreased with age and wear-time adjusted SB increased seems to support this rationale.

The total time spent in PA of all intensity was lower than presented for older people by Buman *et al.* [56] and Davis *et al.* [32]. When comparing the amount of TPA and WT-PA presented in our studies to others, the cohort presented here has fairly low PA. Harris *et al.* [150] reported twice the TPA that was found and a recent Portuguese study [151] also reported higher WT-PA then reported here. Also, average WT-PA has been reported as much as twice as high as in the present study [6, 152]. Some of these differences may be explained by the higher mean age of the participants in the present study compared with the others, but in the current study it was shown PA declines with age, which was similar to existing literature [32, 56, 153]. There was a significant age-group decline in all intensity types of PA (LLPA, HLPA and MVPA), similar to results presented by Buman *et al.* [56], despite minor differences in how activity categories were defined compared with our definition. When comparing the results on WT-PA to a group of older adults with very similar mean age, Davis and Fox *et al.* [154] also reported an average WT-PA intensity that was twice as high as found in the current study. Likewise, in another more recent study by Davis *et al.* [32], WT-PA was also considerably higher in all age groups, except for the oldest group (≥85 years). It should though be taken into consideration, that the average wear-time for each age-group was a bit higher than presented in the current study.

Sedentary time was somewhat higher than has been reported for other older populations [9, 53, 56, 83, 151], but SB is known to have the highest prevalence of all activity types in older adults compared to any other age group [9, 32, 152]. Time spent in SB, as a proportion of wear-time, increased by age, which is in line with former studies [9, 51, 56, 154]. On the other hand, when looking

at hours spent in SB, the sedentary time remains the same for all age-groups which is similar to Davis *et al.* [32] and Sartini *et al.* [34], except they showed the oldest age-group to be most sedentary.

We observed a gender difference in SB as a proportion of wear-time and in hours spent in SB, with men engaging in more SB, which is comparable to former studies [21, 32, 51, 53, 153, 154]. Gender difference was also observed in TPA, but not in WT-PA. In the NHANES study, sex differences in accelerometry data was quite large, with male averaging 10-30% greater WT-PA during wear-time than women [6]. But in a two more recent Norwegian studies, Hansen *et al.* [51] and Lohne-Seiler *et al.* [53] reported no gender difference in WT-PA in older adults. When looking at gender difference in different intensity categories, we see that older women spend more time in light PA, but less time in MVPA compared to men. In agreement with our results, several accelerometer-assessed studies have indicated that men engage in more MVPA [32, 51, 53, 153, 154], but interestingly, one Japanese study has shown an opposite gender difference, where older women engaging in more MVPA compared to men [83]. Also, a gender difference has been observed in light PA, where women spend more time in lower intensity PA [51, 53, 153], but these differences has though been shown to vary by age [53].

Even though gender difference in PA seems to be obvious, it has been suggested that gender differences in free-living data should be interpreted with caution, as a portion of the difference may reflect a difference in measurement rather than an underlying behavior [155]. It was shown by van Domelen *et al.* [155] that older men accumulated greater vertical axis counts/s during walking, than older women. This might be explained by the fact that as gate characteristics and anthropometric measures highly depend on gender [156, 157], they could contribute to gender differences in accelerations produced at the hip while walking.

Seasonal changes

It can be further speculated that the low PA levels might be due to environmental factors which were studied in the second paper to quantify that. During the summer where day length is much longer and ambient temperature is somewhat warmer, more time was spent in all PA categories (2.8-17.2%) and less time in SB (0.4-1.2%). Interestingly, MVPA did not change with seasons. LSPA bouts of minimum of 5 min duration were chosen in our study for comparison with 10 min bouts of MVPA. Our results show that half of the high active participants achieved at least one bout of ≥10 min of MVPA over all valid days measured during either summer or winter, but less then 10% of the low active participants achieved this. When looking at LSPA, most of the high active participants achieved at least one bout of ≥5 min of LSPA, during both seasons, while it goes down to 58% in the low active participants during the winter. Taking together, it was observed that a general shift from sedentariness to life-style activities from darker winter months to the lighter and milder summer months, supporting our rationale that the unique Iceland environmental factors might be contributing to lower PA in this cohort.

The results on seasonal changes in PA showed that there was significantly more PA during the summer than during the winter despite low activity during both seasons, where either day light or temperature explained the seasonal differences. The difference in PA (around 18,000 counts × day^{-1})

was not as large as might have been expected concerning the large difference in day light between the seasons (around 7.5 hours). However, the difference in temperature between seasons is much less than can be expected in many other countries [145]. Using accelerometry assessed data, young to middle-aged adults in the UK [101], women in the US [95] and older adults in the UK [32] and Japan [94], were shown to have a seasonal difference in PA, with less time spent in PA during the winter. Step count in UK adults decreased during the winter [96, 99] and the same was shown in a study of US adults [97]. Self-reported data has also shown a decrease in PA during the winter in UK adults [93], US adults [90] and in Canadian adults [158]. This is confirmed in the current study, which also showed PA to be higher during the summer and, also, with more day-to-day variation in PA.

Participants spent most of their PA time in the LLPA intensity category, both during summer and winter and followed by LSPA intensity, with a maximum of only 40 minutes × day^{-1} during the summer for men and less for women. LLPA tends to be accumulated by incidental activities, like shopping and walking at low pace [101], while LSPA is accumulated by more structured activities like walking, vacuuming and cleaning [38, 152]. This distribution of activity is similar to previous accelerometry-based studies in older adults [32] and younger women [95] in which less time was spent in light intensity PA during the winter.

In the present study, most of the PA occurred from noon till 4 p.m. for both genders and all age groups, except for men in the oldest age group. Conversely, others have reported that older persons are active earlier in the day, or around 10 am [32, 34, 154]. The difference in the timing of PA could possibly be explained by the fact that Iceland is constantly on daylight saving time. Because of this, the solar noon is 1:30 pm in Reykjavik. As the PA in our and the other studies [32, 34, 154] seems to peak around solar noon, the late solar noon in Reykjavik explains at least to some extent different daily pattern of activity in older Icelanders.

Sedentary behavior, as a proportion of wear-time, was greater during winter than summer and overall was quite high, around 75% of wear-time or >10 hrs × day^{-1}. Men spent more time in SB compared to women, both during summer and winter. Seasonal changes in SB have been observed in younger adults [95, 101] and in the study by Buchowski *et al.* [95], women increased their SB by 35 min × day^{-1} during the winter. Comparable accelerometry studies [32, 53, 56] that show seasonal changes in SB in older adults have not been published.

In a country like Iceland, that has extreme weather conditions, creating PA friendly environments that help overcome difficult conditions might contribute to year-long PA participation. In Iceland, which usually has a significant snowfall during the winter, snow and ice accumulation on sidewalks increases the risk of falls and can make walking more challenging, particularly for those with mobility constraints [159, 160]. Thus, immediate snow and ice removal from sidewalks is important, because it may act as a barrier to outdoor activity [158] and increases the fear of moving outdoors, which is common in older people [161]. Sufficient lighting along sidewalks and in parks to overcome fewer hours of daylight during the winter could also support walking and other outdoor PA [158].

Sleep

It is know that sleep is critically important for health, and the same environmental factors that impact PA might also play roles in sleep, which was the focus of the third paper (Paper III). Despite of evidence that sleep duration and quality tends to reduce with increased age [106-108], the free-living sleep data collected using sleep watches (wrist-worn actigraphy) revealed that older Icelandic men and women slept about 8 hours per night, which was surprisingly long. The sleep efficiency (around 80%) and the awakenings per night (around 43) were similar to elderly populations in other countries. Interestingly, men rose about 35 minutes earlier than women, although bedtimes were similar across sexes, resulting in a significantly shorter sleep duration for men. It was also discovered, that while the total hours of daylight were significantly related to sleep timing and duration (about 20 minutes shorter in the summer vs. winter), that were not associated with sleep quality. The interpretation made of these unique findings of surprisingly long sleep duration in older Icelandic men and women, in both summer and winter, is that they seem to be well-adapted to drastic changes to day length changes in Iceland between seasons.

The participants in the study had a longer total sleep time compared to other studies [112, 115, 162]. A study by Blackwell *et al.* [162] using objective sleep monitors in a generally healthy, older, free living men in the US, showed total sleep time to be more than one hour less than measured in the Icelandic men, or 6.4 hours compared to 7.7 hours. The sleep efficiency was similar between those two studies (78.1% vs. 80.9%), but the WASO time was more than double found here (78.4 min vs. 33.0 min). In another objective study [112], focusing on older women living in the US, Icelandic women appeared to have longer total sleeping time (6.8 hours vs. 8.1 hours), and only half of the WASO (65.9 min vs. 30.0 min) compared to the US women. In a more recent objectively measured study on sleep [115], conducted on healthy older women living in Pittsburgh, the total sleep time was 6.6 hours, which is also less total sleep time compared to our Icelandic women. The results suggest that the total sleep time in the cohort is around one hour longer than in comparable cohorts measured with objective methods.

More than one third, or 38% of the participants reported the use of sleep-inducing medication or anti-depressant (including 11% antidepressant use, 12% benzodiazepine use, and 24% other sleep medication use), which is higher compared to the studies mentioned earlier (Lambiase, *et al.* [115] reported 9% using sleep medication; Spira, *et al.* [112] reported 7% antidepressant use and 4.8% benzodiazepine use; Blackwell, *et al.* [162] reported 7.9% antidepressant use, 4.5% benzodiazepine use, and 2.0% other sleep medication use). This high prevalence of sleep medication use may contribute to the long sleep duration seen in this cohort. However, when looking at those who did not use any sleep medication, their average sleep duration was still longer than has been reported earlier [112, 115, 162]. As there is no obvious biological reason for this difference in sleep duration, it is possible that this long sleep duration in this Icelandic cohort is due to some cultural traditions among elderly people in Iceland. It may also question the need for the observed high prescription rate of sleep medication in this Icelandic cohort.

The results revealed that total hours of daylight had a statistically significant relationship with sleep timing and duration. However, the hours of daylight were not associated with sleep quality or PA patterns. Furthermore, no differences were observed in the total sleep time, WASO, or sleep efficiency during the winter, suggesting that the older population studied here is able to adapt sleeping habits and PA patterns to accommodate the change in daylight across seasons. These findings are similar to a Norwegian population study on adults, conducted by Sivertsen *et al.* [163] where the latitude was equal to that of Iceland. In that population study of over 43,000 participants, their self-reported time in bed was not related to the length of daylight. Conversely, a self-report study conducted by Friborg *et al.* [164] examined summer and winter sleep patterns in 150 Norwegian (69^{o}N) and 180 Ghanese (5^{o}N) young men and women and found that the Norwegians rose 32 min later, had longer onset latency, and a slightly reduced sleep efficiency but no change in total sleep time in winter, while sleep patterns of the Ghanese were unchanged from winter to summer [164].

The results indicated that PA had small, but significant impact on onset latency and bed time. Experimental evidence has suggested that exercise may be associated with better sleep quality [104, 118, 165, 166] and that in those with sleep difficulties, exercise may be effective at improving sleep outcomes. Nonetheless, there is a need for additional research to define the direction of these associations, i.e. if improving sleep quality or duration contributes to increasing PA, and conversely, if modifying PA levels has the ability to improve sleep characteristics [104]. Given the multidimensional nature of both sleep and exercise and their impacts on nearly every system of the human body, it is unlikely that the effect of exercise on sleep is influenced by only a single baseline characteristic or transmitted by a single mechanism [166].

Brain measurements

It was of interest to explore potential links between the features of PA and SB that we quantified with detailed biophysical parameters that were obtained in the AGES-Reykjavik study. In the fourth paper (Paper IV), the focus was in addressing whether brain atrophy and PA was linked. Using 5-year longitudinal MRI-derived data, it was found that participants with lower GM and lower WM had less TPA than those with higher GM and WM. Also, those with lower GM and WM had more SB per day compared to those with higher GM and WM. Moreover, the results also showed that less brain volume at baseline and more 5-year loss in brain volume are also associated with less PA and more SB, even after adjustment for self-reported PA at baseline.

Previous longitudinal studies have shown higher PA and structured exercise to be associated with more global or regional brain volumes later in life, both GM and WM [133-135, 167] and as our results may suggest, the longitudinal relationship between brain volumes and PA could also be the other way around, i.e. brain atrophy associates with subsequent decline in PA. Interestingly, two longitudinal studies found no association between PA and brain volumes after adjusting for confounding factors [134, 135]. However, in both studies the participants were slightly younger than in the present study. Because of the adjustment for PA measured at baseline (SPA), the observed

association between brain volumes and brain volume changes on the one hand, and PA at follow-up on the other hand, are independent of the SPA classification at baseline.

It was also shown that, less WM at follow-up and the 5-year change in WM were independently associated with more SB, also after adjusting for lifestyle PA, wear-time, SPA and other potential confounding variables. A recent study on older adults, Burzynska *et al.* 2014 [168], also suggested that the structural integrity of WM was not only dependent on levels of PA, but also on the amount of time spent in SB. This is something that is worth taking note of, because of the high time spent in SB in the cohort.

5.2 Strengths and limitations of the study

The main strength of our studies is the use of objective measurements to assess PA, SB and sleep. As mentioned earlier, the use of objective measurements is thought to be a better option than questionnaires, which tend to overestimate or underestimate PA levels and SB [18, 19]. Another strength is that the findings of our studies are based on a well-characterized large-population-based cohort of older Icelandic adults, which included detailed assessments of their health status over the past 45 years. Concordant measurement of objective sleep and PA is also rare, particularly in older populations [115]. And, unlike previous studies of this nature, we were able to compare the sleep patterns and qualities between men and women, and explore multiple factors that are thought to influence sleep. Due to Iceland's unique geographical location, which provided a relatively large variation in daylight, we were able to investigate the relationship between day length and free-living sleep-patterns in older adults more extensively. We were also able to use within-individual comparisons of sleep and PA patterns gained by repeating measurements in an opposite daylight condition to confirm cross-sectional findings that season had a statistically significant, although practically minor impact on sleep patterns and quality in this population. Also, were we able to include objectively measured PA at follow-up and had a longitudinal design of brain measurements with five years interval.

The compliance in all four studies was very high. In paper I, 86% of the participants had four or more valid days of PA measurements. In Paper II, 88.4% of the participants had four valid days of measurements. In Paper III, nearly 100% had six or more valid days of sleep measurements and 79% had six or more valid days of PA measurements. In Paper IV, 87% of the participants had four or more valid days of PA measurements.

A limitation of the studies is that accelerometers miss some movement patterns, like upper body movements during activities like heavy carrying and lifting. Also, they are limited on detecting non-ambulatory activities like cycling [13] and water activities like swimming [20]. However, in Iceland cycling is not common in this age group [169]. Swimming is a quite popular exercise form in Iceland. As the accelerometer cannot be worn during swimming, this activity is not included in the accelerometer data. About quarter of all participants reported swimming as an exercise both during summer and winter, but of those who swim, only 25% swim for >30 min each time. This is similar to a

British cohort from a study by Martin *et al.* [170], but quite higher compared to a study conducted in the US [171]. In the current study, those who reported swimming as an exercise also had more TPA and WT-PA than those that did not report swimming as an exercise.

Another limitation is that while we did find that factors such as age, gender, length of daylight, BMI and PA levels to be independently associated with cross-sectional differences in sleep patterns (bed time, rise time, rest and sleep durations) and sleep quality (total sleep time, efficiency, WASO, and number of awakenings), we could not state with certainty that any causal relationships exist. Self-reported health status had little influence on sleep patterns. However, studying a mostly healthy population may have limited our ability to draw conclusions that relate health status to sleep patterns and it does not permit us to investigate other important relationships between sleep and health in patients with clinical conditions common to older individuals. Thus, the question of whether sleep patterns and quality impact future health remains to be answered with further follow-up in this cohort and in future studies that are designed to address these questions. Moreover, the cohort that we studied consisted of subjects between 73 and 91 years of age. The older age and healthy status could partly explain the longer sleep time and limited influence by outdoor daylight variations. The usage of sleep medication was high in the Icelandic population we studied and, along with the health status, was assessed using self-report during the participants' first visit. Therefore, it is not known whether the participants changed medication usage, or health status, between visits. However, in the cross-sectional sample, neither sleep medication use nor health status was related to day length, suggesting that it may be consistent throughout the year. Lastly, we only analyzed the night sleeping patterns and excluded naps.

The main limitation of Paper IV was that PA at baseline was not measured by an objective method, as self-report questionnaires were used. Therefore, we did not have similar measurements of the PA and SB at baseline and at follow-up, and SB was not measured at baseline. It is possible that if objective measurement of PA at baseline would have been available and used to adjust the statistical models, the observed association would have become smaller. A longitudinal study using objective measurements both at baseline and follow-up would be beneficial to further test our hypothesis. Since we only have objective measurements at follow-up, it is unclear if the relationships observed are uni- or bi-directional. Other studies are necessary to identify the direction of these relationships.

6 Conclusions

In this dissertation, for the first time, insights of the PA and sleep patterns using objective measurements in healthy Icelandic older adults are established. This enables clinical, epidemiological, environmental, and sociological questions to be asked regarding how activity levels, patterns, and sleep quality are associated to each other, how they might change with the environment, and ultimately linked to healthy aging. When older adults stop working and retire, more opportunity should come up to be physically active and maintaining recommended levels of PA. The increase in time spent in SB after the age of 60 has been thought to be a cause of positive factors such as increased leisure time following retirement or negative factors such as worsening health conditions [9]. Retirement has been recognized as a major life event, which should be used to try to influence the PA in older adults [172], even though mixed results have been extracted on how retirement affects PA [173-175]. This event in the life of an older adult could be a good target point for policy makers for introducing the importance of active lifestyle in older age, and create new traditions. But in the end, the responsibility lies with the older individuals itself. To be able to live a happy and healthy life, everyone needs to take a responsibility for their own health.

From a public health perspective, advancing knowledge with regard to factors that may interrupt PA is necessary for better understanding and then possible intervention planning. As the population is getting older by every year [1], it may be important to intervene this trend of low PA and get older people to diminish their SB. It is possible that they can then live more independently and increase the quality of life in their older days. This is supported by the observed association between PA, SB and brain atrophy in the current study.

The initialization of this study marked the beginning of the continuing efforts to understand how daily PA plays a role in the health of Icelanders, especially the older populations. The longevity of the population living at high latitude, and the general benefits of PA to health would seem to suggest that those older healthy Icelanders live an active lifestyle. However, the observation that the PA level was generally low did not support that simple rationale. This could be due to multiple factors, such as normal aging and environmental restrictions (day length and temperature) as has now been discovered for the first time. The small changes in PA, SB, sleep patterns and quality observed during periods of disparate daylight length, suggest that this population is well adapted to the seasonal variation of daylight in Iceland. Nevertheless, in studies on PA and SB in older people, it is important to consider seasonal differences during data collection and in analysis of data. The long sleep time in the cohort is further revealed here. These results raise the following question: Would, by increasing PA in older Icelanders, increase the quality of their sleep and lead to less need a for long sleep time? Would this then positively influence brain atrophy, resulting in a positive influence on PA? By intervene the pattern of low PA and long sleep time, would a better overall health could possibly be gained. Or is this high sedentary time in this cohort a protective factor for longevity? Further researches are needed to address why this cohort of older adults live as long as they do, even they spend the majority of their day as sedentary.

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Paper I

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Objective measurements of daily physical activity patterns and sedentary behaviour in older adults: Age, Gene/Environment Susceptibility-Reykjavik Study

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Abstract

Background: objectively measured population physical activity (PA) data from older persons is lacking. The aim of this study was to describe free-living PA patterns and sedentary behaviours in Icelandic older men and women using accelerometer.

Methods: from April 2009 to June 2010, 579 AGESII-study participants aged 73–98 years wore an accelerometer (Actigraph GT3X) at the right hip for one complete week in the free-living settings.

Results: in all subjects, sedentary time was the largest component of the total wear time, 75%, followed by low-light PA, 21%. Moderate-vigorous PA (MVPA) was <1%. Men had slightly higher average total PA (counts × day^{-1}) than women. The women spent more time in low-light PA but less time in sedentary PA and MVPA compared with men ($P < 0.001$). In persons <75 years of age, 60% of men and 34% of women had at least one bout ≥10 min of MVPA, which decreased with age, with only 25% of men and 9% of women 85 years and older reaching this.

Conclusion: sedentary time is high in this Icelandic cohort, which has high life-expectancy and is living north of 60° northern latitude.

Keywords: *physical activity, accelerometry, sedentary behaviour, older adults, BMI, AGES-Reykjavik, older people*

Introduction

Physical activity (PA) is an important indicator of health [1] and overall PA level decreases with age [2]. In old age, low PA has been linked with reduced physical functioning, such as mobility limitation [3], which is one of the most important factors in maintaining an individual's independence [4]. Sustained PA over the lifespan has been shown to have protective effects on mobility, even in those who start participating in PA at a later stage in life [5].

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In epidemiological studies, PA has often been assessed by self-report measurements. Self-reports can be helpful but tend to overestimate true PA and underestimate sedentary time [6, 7]. Light PA is the most difficult intensity category to recall or remember accurately [8, 9]. However, light PA is the most common intensity category for the activities in which older adults engage [7, 10]. Although other measures exist for assessing overall energy expenditure (doubly-labelled water) and for the assessment of activity type and context (surveys and diaries), accelerometers are useful tools to explore patterns of PA objectively in terms of the elemental characteristics such as intensity, duration and frequency [11, 12]. Accurate assessments of PA levels and patterns, using objective portable activity monitors (pedometers and accelerometers), have been shown to be sensitive and feasible for measuring general activity patterns in older adults [13]. Although the accelerometer has been used extensively to assess PA in other age groups [2], it has been sparsely utilised in older populations.

The AGES-Reykjavik study (Age, Gene/Environment Susceptibility Reykjavik Study) has investigated the contributions of environmental factors, genetic susceptibility and gene–environment interactions to ageing of the neurocognitive, cardiovascular, musculoskeletal, body composition and metabolic systems in population with high life-expectancy [14]. The AGES-Reykjavik cohort was recruited from survivors of the Reykjavik Study. Data collection on the original Reykjavik Study cohort dates back to 1967 and there have been two waves of data collection for the AGES-Reykjavik studies, separated by 5 years (AGES-Reykjavik in 2002–06 and the AGESII-Reykjavik study in 2007–11). In this well-characterised population, the goals of this study are: (i) to assess free-living PA patterns in a subsample in the AGESII-Reykjavik study with accelerometers; (ii) to investigate the features of PA and sedentary patterns in the same study with respect to age, sex and body mass index (BMI). This study is, to our knowledge, the first one to objectively measure PA using accelerometry in a large, well characterised cohort of older people living north of 60° northern latitude.

Methods

Participants and protocol

This study was a part of the AGESII-Reykjavik study which is a follow-up of the AGES-Reykjavik study. Between April 2009 and June 2010, objective PA measurement by accelerometers was added to the AGESII-Reykjavik study protocol. Details on the study design and the baseline AGES-Reykjavik assessments have been described elsewhere [15].

During the PA measurement period, 1,194 subjects participated in the AGESII-Reykjavik study (73–98 year old). For the PA measurements, participants ($n = 55$) were excluded due to cognitive impairment (MMSE <20), as those participants were not expected to be able to reliably wear and use the accelerometer [16], 95 were excluded for other reasons (e.g. blindness and other physical obstructions), 84 refused and 294 did not participate because of scheduling conflict. The remaining 671 (56.2%) participants received an accelerometer to measure their daily activity. Five monitors were lost and 12 files were unusable because of device failures. The final number was 579 participants who had four or more valid days (≥10 h of wear time) of accelerometry data. The study was approved by the Icelandic National Bioethics Committee (VSN: 00–063), the Icelandic Data Protection Authority, and the institutional review board of the US National Institute on Aging, National Institutes of Health. Signed informed consent was given by all participants.

Measurements and data analysis

Participants were asked to wear the ActiGraph activity monitors (model GT3X ActiGraph, Inc., Pensacola FL, USA) monitor at the right hip for 7 days and to remove the monitor only before going to bed and during showers, bathing or other water activities. Also, participants completed a self-reported questionnaire on swim habits. To explore the general patterns of PA, we only report the data in the vertical axis. Activity intensity categories were defined as: sedentary, low-light intensity, high-light intensity and, moderate to vigorous intensity (see Table 1 for cut-points). Please see Supplementary data available *Age and Ageing* online, Appendix S1.

Results

Subject participation

Detailed demographic and anthropometric characteristics of subjects are presented in Table 1. There were no significant differences between men and women in age and BMI ($P = 0.23$ and 0.69, respectively) and no difference in total PA (counts × day^{-1}) between different educational levels ($P = 0.21$), data not shown. Participants who wore the accelerometers had similar subject characteristics compared with those participants who did not receive an accelerometer: average values (SD) for men who did not receive an accelerometer; age = 81.8 year (5.1), weight = 83.0 (13.6), BMI = 26.7 (4.0) and for women who did not receive an accelerometer; age = 81.2 year (5.4), weight = 70.8 (12.3) and BMI = 27.3 (4.6).

Sex differences

The detailed summary of the PA is shown in Table 1. Men had 18 min longer average daily wear time than women ($P = 0.024$). While the average PA level during the valid days among participants varied widely (9,300–400,000 total PA (counts × day^{-1}); 15–491 wear time PA (counts × min^{-1})), men had slightly higher average PA than women (total PA: $P = 0.048$; wear time PA: $P = 0.092$). Sedentary time was the largest component of the total wear time (74.5%), followed by low-light PA (21.3%) and MVPA

Table I. Descriptive statistics for subjects with four or more days with 10 or more hours of wear time

Variable	Men		Women		*P*-value
	n	Mean (SD)	*n*	Mean (SD)	
Age (years)	221	79.7 (4.2)	358	80.2 (5.1)	0.23
Weight (kg)	220	83.2 (14.2)	357	70.1 (13.6)	<0.001*
BMI (kg × m^{-2})	220	26.7 (3.9)	357	26.8 (4.8)	0.69
Valid wear time (min × day^{-1})	221	832 (92)	358	815 (83)	0.024*
Age groups					
≤74.9	53	859 (96)	73	837 (78)	<0.001**
75–79.5	76	831 (91)	130	833 (90)	
80–84.9	64	818 (77)	90	802 (77)	
≥85	28	816 (109)	65	773 (65)	
BMI groups					
Normal weight[c]	77	835 (102)	132	816 (75)	0.17
Overweight[c]	97	823 (82)	141	814 (88)	
Obese[c]	46	843 (95)	84	816 (89)	
Total PA (1,000 counts × day^{-1})	221	117 (68)	358	105 (58)	0.048*
Age groups					
≤74.9	53	146 (67)	73	130 (71)	<0.001**
75–79.5	76	125 (67)	130	116 (55)	
80–84.9	64	95 (61)	90	94 (45)	
≥85	28	89 (60)	65	72 (41)	
BMI groups					
Normal weight	77	128 (78)	132	113 (61)	<0.001***
Overweight	97	114 (64)	141	103 (56)	
Obese	46	106 (56)	84	97 (53)	
Wear time PA (count × min^{-1})	221	139 (78)	358	128 (65)	0.092
Age groups					
≤74.9	53	171 (77)	73	154 (80)	<0.001**
75–79.5	76	150 (78)	130	139 (62)	
80–84.9	64	115 (69)	90	116 (51)	
≥85	28	106 (67)	65	92 (52)	
BMI groups					
Normal weight	77	152 (89)	132	137 (69)	<0.001***
Overweight	97	137 (74)	141	125 (63)	
Obese	46	125 (63)	84	119 (62)	
Sedentary time (hours × day^{-1})[a]	221	10.5 (1.5)	358	10.0 (1.3)	<0.001*
Age groups					
≤74.9	53	10.5 (1.8)	73	9.9 (1.4)	0.15
75–79.5	76	10.3 (1.5)	130	10.0 (1.5)	
80–84.9	64	10.7 (1.3)	90	10.0 (1.3)	
≥85	28	10.7 (1.7)	65	10.2 (1.1)	
BMI groups					
Normal weight	77	10.5 (1.6)	132	9.9 (1.2)	0.13
Overweight	97	10.3 (1.4)	141	10.0 (1.4)	
Obese	46	10.7 (1.5)	84	10.3 (1.5)	
Sedentary time (percent × weartime^{-1})[a]	221	75.9% (8.3%)	358	73.9% (8.6%)	0.001*
Age groups					
≤74.9	53	73.5% (8.8%)	73	71.5% (9.2%)	<0.001**
75–79.5	76	74.3% (7.8%)	130	72.1% (7.7%)	
80–84.9	64	78.2% (7.4%)	90	75.0% (8.2%)	
≥85	28	79.0% (8.2%)	65	78.9% (7.9%)	
BMI groups					
Normal weight	77	75.8% (8.2%)	132	72.9% (8.7%)	0.002***
Overweight	97	75.5% (8.6%)	141	73.8% (8.8%)	
Obese	46	76.7% (7.7%)	84	75.5% (8.0%)	
Low-light PA (min*day^{-1})[b]	221	163 (55)	358	182 (60)	<0.001*
Age groups					
≤74.9	53	178 (63)	73	197 (64)	<0.001**
75–79.5	76	169 (50)	130	198 (53)	
80–84.9	64	150 (51)	90	175 (59)	
≥85	28	148 (56)	65	145 (55)	
BMI groups					
Normal weight	77	161 (56)	132	189 (62)	0.012***

Continued

Table 1. Continued

Variable	Men		Women		*P*-value
	n	Mean (SD)	*n*	Mean (SD)	
Overweight	97	165 (56)	141	184 (61)	
Obese	46	163 (54)	84	171 (54)	
High-light PA (min × day^{-1})[c]	221	29 (22)	358	27 (23)	0.23
Age groups					
≤74.9	53	35 (22)	73	36 (28)	<0.001**
75–79.5	76	34 (25)	130	30 (23)	
80–84.9	64	21 (18)	90	24 (16)	
≥85	28	19 (16)	65	17 (18)	
BMI groups					
Normal weight	77	28 (19)	132	28 (23)	0.028***
Overweight	97	30 (25)	141	27 (24)	
Obese	46	29 (22)	84	25 (22)	
MVPA (min*day^{-1})[d,f]	221	9.9 (13)	358	5.0 (7.2)	<0.001*
Age groups					
≤74.9	53	14.5 (15.0)	73	7.6 (9.6)	<0.001**
75–79.5	76	10.0 (11.7)	130	5.6 (7.5)	
80–84.9	64	7.4 (12.6)	90	3.7 (5.1)	
≥85	28	6.8 (10.3)	65	2.3 (4.0)	
BMI groups					
Normal weight	77	13.9 (17.2)	132	6.3 (8.1)	<0.001***
Overweight	97	8.4 (9.5)	141	4.1 (5.6)	
Obese	46	6.6 (8.6)	84	4.3 (7.7)	

Genders compared by *t*-test; for PA and sedentary variables *t*-tests were conducted on square root transformed data. PA measured by sex, age group and BMI. For cut-points see Troiano *et al.* [2] and Matthews *et al.* [17].

[a]0–99 counts/min.

[b]100–759 counts/min.

[c]760–2,019 counts/min.

[d]≥2,020 counts/min.

[e]Normal weight BMI < 25kg × m^{-2}, overweight BMI = 25–29.9 kg × m^{-2}, obese BMI ≥ 30 kg × m^{-2}.

[f]Of the 579 participants, 25 (4.3%) had zero minutes of MVPA, 10 (4.5%) men and 15 (4.2%) women.

*Significant difference between genders ($P < 0.05$).

**Significant correlation with age, adjusted for BMI and gender (multiple linear regression).

***Significant correlation with BMI, adjusted for age and gender (multiple linear regression).

(1%) in the participants as a group. Women spent more time in low to-light PA and less in MVPA compared with men, but had less sedentary time compared with men (all $P < 0.001$). The average time spent in MVPA per week was 9.9 min/day for men and 5.0 min/day for women.

Age differences

In both men and women, except for sedentary time, the PA variables total PA, wear time PA, low-light PA, high-light PA and MVPA decreased progressively with advancing age (Table 1). In the <75 years age group, 60% of men and 34% of women had at least one bout ≥10 min of MVPA (MVPA10+) during PA measurements (Figure 1). This proportion declined with age, and only 9% of the women and 25% of men in the >85-year age group had at least one bout of MVPA10+.

BMI differences

Except for sedentary time, BMI was negatively related to all PA variables. Furthermore, multiple linear regression analysis, using BMI and age as continuous variables, showed that the association of BMI and the PA parameters was independent of age and gender (Table 1). The proportion of subjects having at least one bout of MVPA10+ during PA measurements also declined with an increasing BMI (Figure 1).

Average daily PA patterns

Within an average day, the majority of the PA occurred during the hours between 8 a.m. and midnight (Figure 2). In all age groups, there was a significant ($P < 0.001$) sex difference in within-day PA variation. *Post hoc* analysis (Bonferroni) indicated that men were more physically active than women between both 4 a.m.–8 a.m. and 8 a.m.–noon, Also, there was a significant difference in within-day PA variation and age groups ($P < 0.001$), which is explained by more decline in PA with increasing age during the day than during the night. Further examination showed the relative decline in PA with age to be very similar for all day hexiles, except for the midnight–4 a.m. hexile that show relatively more decline in PA with age than the other day hexiles.

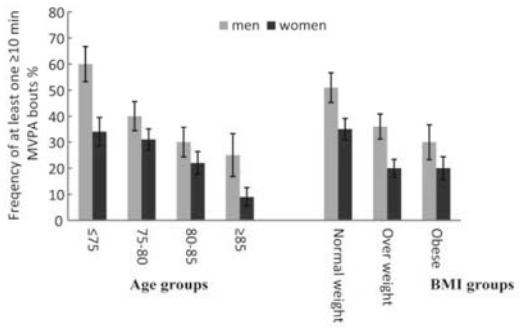

Figure 1. Proportion (SEp) of subjects with more than one MVPA10+ bouts by age groups and gender ($n = 579$; men = 221, women = 358) and by BMI categories and gender ($n = 577$; men = 220, women = 357).

Day of week effects

There was a significant difference in activity by day of the week when adjusted for difference between subjects ($P < 0.001$). Participants were significantly less active on Sundays (total PA 98×10^3 counts $\times$ day^{-1}) compared with other days of the week (114×10^3 counts $\times$ day^{-1}; TukeyHSD: $P < 0.001$). Saturdays also had less activity than Wednesdays and Thursdays. Age and gender distribution of valid accelerometer data was the same for all days of the week.

Self-reported swim habits

About quarter of all participants reported swimming as an exercise, both during summer and winter, but of those who swim, only 25% swim for >30 min each time. Those who reported swimming as an exercise, also had more total PA and wear time PA (total PA: 121×10^3 counts $\times$ day^{-1} for swimmers vs. 91×10^3 counts $\times$ day^{-1} for non-swimmers; $P < 0.001$). Men used swimming more as an exercise compared with women, both during summer and winter (Chi-Square: $P < 0.001$). There was no age group difference in using swimming as an exercise during the winter ($P = 0.069$), but an age group difference was present during the summer ($P = 0.013$).

Discussion

The main finding of this study is that older adults spend on average 74.5% of their non-sleeping time as sedentary and 21.3% as low-light activity, indicating that this age group has very low activity. Furthermore, the PA is reduced as age and BMI increase. Women spend more time in low-light activity than men, where men had more MVPA than women.

Sedentary time, as proportion of wear time, was somewhat higher than has been reported for older populations

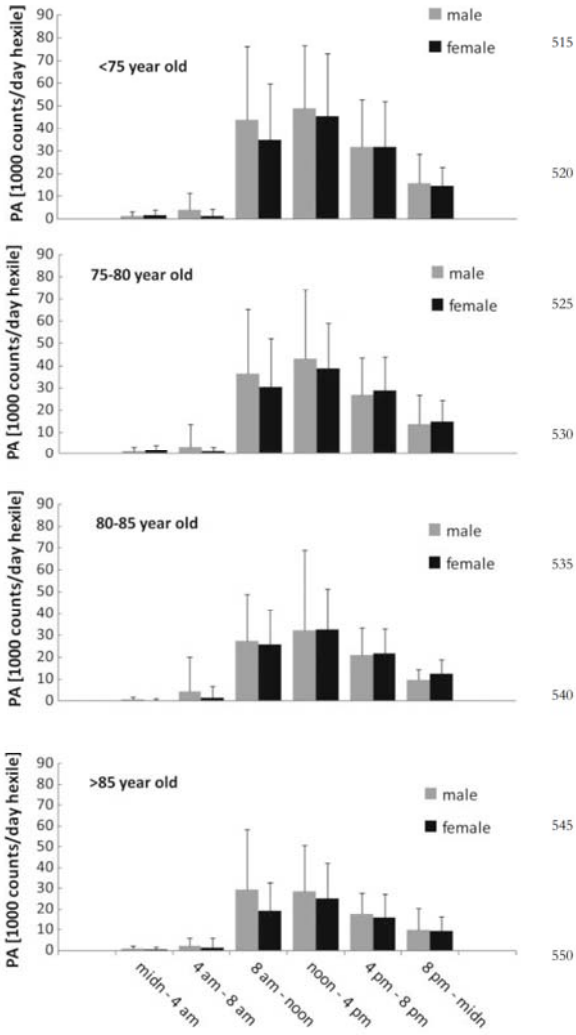

Figure 2. Distribution of PA between day hexiles (4 h periods) for different age groups and sexes. Beside a significant difference in PA between different day hexiles ($P < 0.001$), ANOVA for repeated measures (on square root transformed data) showed significant interactions of the within-day distribution of PA with both gender ($P < 0.001$) and age groups ($P < 0.001$); three-way interactions were non-significant ($P = 0.65$).

[17, 18]. Harris *et al* [19] reported more than twice the total PA than we found (mean age 74 years). Also, average wear time PA has been reported around twice as high than in the present study [2, 20, 21]. Some of these differences may be explained by the older mean age of the participants in our study compared with the others. However, Davis and Fox [22] studied a group of older adults with a similar

mean age and reported an average wear time PA intensity that was twice as high as that found here. In a recent study, PA was considerably higher in all age groups, except for the oldest group [23]. MVPA accumulated in our cohort, is only about half what has been previously shown for this age group [18, 22]. Furthermore, relatively fewer participants in our study reach at least one MVPA10+ bout per day as has been reported before [22].

Our results indicate that most older adults fail to meet general recommendations for PA, i.e. 30 min of MVPA each day [9, 24]. Older individuals find it difficult to take part and maintain MVPA [25, 26]. Therefore, more frequent periods of rest between bouts might be required for them to accumulate enough PA to meet recommendations. As Buman *et al.* [18] pointed out, it may be more realistic to focus the recommendations for older individuals on replacing sedentary behaviour by high-light PA rather than on accumulating MVPA. In our study, men accumulate 29 min of high-light PA each day on average and women 27 min.

The low PA level in our cohort can possibly be explained by several factors. It may be partly counterbalanced by swimming activity as a quarter of our cohort reported swimming as an exercise. Also, we have not taken into account seasonal effects. The summer is shorter in Iceland compared with the summer season of locations of comparable studies. Data in our study were accumulated from April to June with a summer-break in July, and then from August to June of the next year. Part of the free-living summer activity was missed. The reason that older adults accumulate low amount of MVPA in our and other studies [18, 22, 23] may also be due to the fact that cut-points were not adjusted according to individual aerobic fitness as should be done according to the recommendations [9, 24]. Factors such as illness and worse physical health may explain some of this reduced activity in older adults. The lack of social support and encouragement from family is an important factor, but fear of getting injured and moving outdoors is common [27, 28]. Icelandic winters can be cold, windy- and icy, so easy access to facilities is important and should be provided. PA pattern earlier in life can also be an indicator of later life activity [29].

The difference between sex and BMI groups in PA we report here is comparable with other previous population data [17–19, 22, 23]. Also, PA and valid wear time declines with age in both men and women which was similar to existing literature [18, 23]. Sedentary time remains the same for all age groups, which is similar to Davis *et al.* [23], except he showed the oldest age group to be most sedentary. Buman *et al.* [18] showed a decrease with age in low-light PA, high-light PA and MVPA, despite minor differences in how activity categories were defined compared with our definition. Sedentary behaviour in the USA, based on NHANES 2003–04, shows a large change from the age 60–69 to 70–85 age groups, where sedentary time is increased by 87 min/day on average [17].

Most of the PA in older Icelandic populations occurred from noon till 4 p.m. for both genders and all age groups, except for men in the oldest age group. Others have reported that older persons are active earlier in the day [22, 23]. The difference in the timing of PA could possibly be explained by the fact that Iceland is constantly on daylight saving time. Because of this, the solar noon is 1:30 p.m. in Reykjavik. As the PA in our and the other studies seems to peak around solar noon, the late solar noon in Reykjavik explains at least to some extent different daily pattern of activity in older Icelanders in comparison with the other studies.

The strength of this study is that the findings are based on a well-characterised large-population-based cohort of older Icelandic adults. However, there are some limitations that need to be accounted for when interpreting the results. It is known that accelerometers miss some movement patterns, like upper body movements during activities like weight lifting and heavy carrying. They also have limitations on detecting non-ambulatory activities like cycling [11]. However, in Iceland this kind of activity is not common in this age group. There might also be a problem measuring older individuals with accelerometers, where the quality of the data depends on participant's compliance [30]. This can be challenging for older persons suffering from some kind of memory loss, but those who were most cognitively impaired were excluded from our study. However, compliance in our study was very high as 86% of the participants had four or more valid days. Overall, the results from this study generally exhibited a low PA level in the population of older Icelanders who live at high latitude with high life-expectancy. This contradicts studies that show PA to reduce mortality and extend life expectancy [31]. The reason for high life expectancy in the Icelandic population may be due to a good health-care system, low infant mortality and high fish consumption [14, 32, 33]. Future studies are needed to further investigate how PA is related to health outcomes and other risk factors of health in this unique population.

Key points

- Very low level of PA in older population who live at high latitude with high life-expectancy.
- PA declines with increasing age and BMI.
- Women spent more time in low-light activity than men, where men had more moderate activity than women.

Conflicts of interest

None declared.

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Supplementary data

Supplementary data mentioned in the text is available to subscribers in *Age and Ageing* online.

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Paper II

Comparison of summer and winter objectively measured physical activity and sedentary behavior in older adults: Age, Gene/Environment Susceptibility-Reykjavik Study

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Abstract

In Iceland, there is a large variation in daylight between summer and winter. The aim of the study was to identify how this large variation influences physical activity (PA) and sedentary behavior (SB). Free living PA was measured by a waist-worn accelerometer in in 138 older adults (61.1% women, 80.3±4.9 yrs) during summer and winter months. In general, SB was high, about 75% of registered wear time and age had the strongest association with SB (β=0.36) and all PA variables (β=-0.32 to -0.44). During the summer, more time was spent in all PA categories, except for the moderate-to-vigorous PA (MVPA), and SB was reduced. More lifestyle PA (LSPA) was accumulated in ≥5 min bouts during summer than winter, especially among highly active participants. Accounting for seasonal difference is neccesary in analyzing SB and PA data.

1. Introduction

The benefits of physical activity (PA) are well known and important for disease prevention and the maintenance of self-support in older adults (Haskell, Lee, Pate et al., 2007). In 2008, US Department of Health and Human Services published guidelines for Americans that recommended older adults to conduct at least 150 min × week^{-1} of moderate intensity PA or 75 min × week^{-1} of vigorous-intensity aerobic PA, or an equivalent combination of moderate- and vigorous PA (US-Department-of-Health-and-Human-Services, 2008). The guidelines state that aerobic PA should be performed in episodes of at least 10 min bouts, which has been supported by other researchers (Altena, Michaelson, Ball et al., 2006; Altena, Michaelson, Ball et al., 2004; Murphy, Blair and Murtagh, 2009; Strath, Holleman, Ronis et al., 2008). However, other studies have shown that health benefits might also be gained with bouts of activity that last less than 10 min (Miyashita, Burns and Stensel, 2008; Strath, Holleman, Ronis et al., 2008) and by avoiding sitting and sedentary behaviour (SB) (Hamilton, Hamilton and Zderic, 2007; Levine, 2007).

Levels of PA tend to change according to seasons in younger adults (Buchowski, Choi, Majchrzak et al., 2009; Clemes, Hamilton and Griffiths, 2011; Dannenberg, Keller, Wilson et al., 1989; Hamilton, Clemes and Griffiths, 2008; Matthews, Freedson, Hebert et al., 2001; O'Connell, Griffiths and Clemes, 2014; Plasqui and Westerterp, 2004; Tudor-Locke, Bassett, Swartz et al., 2004). In 2007, Tucker and Gilliland (Tucker and Gilliland, 2007) reviewed 37 studies conducted between 1980 to 2006, and found that there were significant seasonal changes in moderate-to-vigorous physical activity (MVPA) in 73% of the studies. Reasons for seasonal differences in PA may be changes in daylight hours (Sumukadas, Witham, Struthers et al., 2009), outdoor temperature

(Brandon, Gill, Speechley et al., 2009; Chan, Ryan and Tudor-Locke, 2006; Sumukadas, Witham, Struthers et al., 2009; Yasunaga, Togo, Watanabe et al., 2008), precipitation and wind (Kolle, Steene-Johannessen, Andersen et al., 2009; Togo, Watanabe, Park et al., 2005; Tucker and Gilliland, 2007) that occur throughout the year. Until now, most studies of seasonal changes in PA have been conducted in children, adolescents or young adults (Tucker and Gilliland, 2007). A few studies using objective measurements have shown older people to be less active during the winter (Davis, Fox, Hillsdon et al., 2011; Yasunaga, Togo, Watanabe et al., 2008). However, these studies failed to examine the influence of season on bouted PA, but according to recommendations PA should be performed in bouts of at least 10 min duration (US-Department-of-Health-and-Human-Services, 2008).

The aim of this study was to objectively assess free-living PA and SB patterns comparing summer and winter periods in a sample of older community-dwelling Icelanders from the Age, Gene/Environment Susceptibility Reykjavik study (AGESII study). We measured two one-week assessment periods during the summer and winter months to investigate the seasonal influences on PA and SB patterns, including time spent in different PA intensity catagories and 5 and 10 min bouts. We then examined whether the results were similar in a larger cross-sectional population. To our knowledge, this is the first study to compare seasonal changes in free-living objectively measured PA and SB in an older community-dwelling population, living at a latitude of 64-66°North, where the daylight change is dramatic (4-21 hours) between summer and winter months.

2. Methods

2.1 Study population and design

This study was a part of the AGESII study, a follow-up of the Age, Gene/Environment Susceptibility Reykjavik study (AGES study), which was designed to assess the influence of environment, genetic factors, and gene-environment interaction on various health topics related to aging in a historically healthy, aging population with high life-expectancy (Harris, Launer, Eiriksdottir et al., 2007). The study was initiated with a first wave of data collection from 2002-2006 with 5,764 participants who were recruited from the original Reykjavik Study which collected data on age-related topics, mainly cardiovascular risk factors, since 1967 (Harris, Launer, Eiriksdottir et al., 2007). The second wave of data collection (AGESII study) involving 3,411 participants took place between 2007 and 2011. Between April 2009 and June 2010, objective PA measurement by accelerometers was added to the AGESII study protocol. Details on the study design and the baseline AGES study assessments have been described elsewhere (Harris, Launer, Eiriksdottir et al., 2007). During the PA measurement period, 1,194 subjects participated in the AGESII study (the flow chart for this study population is shown in Figure 1). For the PA measurements, participants (n= 55) were excluded due to cognitive impairment (MMSE <20), as those participants were not expected to be able to reliably wear and use the accelerometer (Tombaugh and McIntyre, 1992), 95 were excluded for other reasons (e.g. blindness and other physical obstructions), 84 refused and 294 did not participate because of scheduling conflicts. Five subjects lost the accelerometers and 12 files were unusable because of device failures. The remaining 649 (54.4%) participants received an accelerometer to measure their daily activity. Of these, there were 590 participants who had four or more valid days (≥10 hours of wear time) of useable accelerometry data. The details of the study has been described elsewhere (Arnardottir,

Koster, Van Domelen et al., 2012). These 590 subjects were used for the cross-sectional analysis of the influence of daylength and temperature on PA and SB patterns.

We also carried out a comparative, paired sub-study of summer-winter PA. Subjects who had worn an accelerometer during warmer months with more hours of daylight (from May 15th to September 30th 2009, termed "summer" for simplicity) were asked to wear the monitor again for a week during the colder months with fewer daylight hours (from November 18th 2009 to March 19th 2010, referred to as "winter"). No measurements were done in July 2009 because of summer vacations and in late December 2009 because of the potential of the Christmas holiday to influence the measurements. Two hundred and nineteen people were asked to participate in the sub-study (one subject had passed away). In total, 160 subjects accepted participation, three device malfunctions led to 157 participants with usable accelerometer data, 138 of which had four or more valid days of measurements in both winter and summer sessions and were used for final analysis. The study was approved by the Icelandic National Bioethics Committee (VSN: 00-063), the Icelandic Data Protection Authority, and the institutional review board of the US National Institute on Aging, National Institutes of Health. Signed informed consent was given by all participants.

2.2 Demographic and Environmental Parameters

Participants came to the Icelandic Heart Association in Kópavogur, Iceland for assessment of cognitive and physical function as part of the AGESII study. Height and weight were taken using standardized procedures and body mass index (BMI) was computed as the ratio of weight and height^2 (kg × m^{-2}). Participants reported overall health status on a discrete scale (1-excellent, 2-very good, 3-good, 4-fair, 5-poor). The hours of daylight of each participant's week of free-living measurement were obtained

using the Sunrise/Sunset calculator provided by the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html). The average daily outdoor temperature over the same period was obtained from the Weather Underground (www.wunderground.com) historical weather data.

2.3 Assessment of PA

Participants were asked to wear the ActiGraph GT3X accelerometer (Actigraph Inc., Pensacola FL) monitor at the right hip for one complete week and to remove the monitor only before going to bed and during showers, bathing, or other water activities. Non-wear was defined as a period of at least 60 consecutive minutes during which the activity monitor recorded zero counts in all axes, allowing 1-2 minutes of vertical-axis counts between 0 and 100. All intervals in a day that did not meet the non-wear criteria were considered wear time. A day of accelerometer wear was considered valid if the wear time was ≥10 hours. Participants with fewer than four valid days over the week of measurement were excluded from further analysis (Troiano, Berrigan, Dodd et al., 2008). To explore the general patterns of PA, we only report the data in the vertical axis and present daily averages of Total PA (TPA) (counts × day^{-1}). Activity intensity categories were defined as: Sedentary behaviour (SB) as hours × day^{-1} of activity <100 count ×min^{-1} during wear time, Low-light PA (LLPA) as 100 -759 counts × min^{-1}, Lifestyle PA (LSPA) as ≥760 counts × min^{-1} (Arnardottir, Koster, Van Domelen et al., 2012; Gennuso, Gangnon, Matthews et al., 2013; Matthews, 2005) and moderate-to-vigorous PA (MVPA) as ≥2020 counts × min^{-1}. To adjust for variable wear times on PA, we also explored each activity intensity category normalized by the wear time (WT-TPA, WT-LLPA, WT-LSPA and WT-MVPA). Standard deviation (SD) variables (SD-Wear time,

SD-SB, SD-TPA, SD-LLPA, SD-LSPA and SD-MVPA) were calculated as SD of the day-to-day variation in respective activities. A bout of MVPA was defined as at least ten consecutive minutes of activity counts above the moderate threshold (≥2020 counts × min^{-1}), allowing for one minute outside of the threshold (Matthews, Chen, Freedson et al., 2008; Troiano, Berrigan, Dodd et al., 2008). A bout of LSPA was defined as at least five consecutive minutes of activity counts above the LSPA threshold (≥760 counts × min^{-1}), allowing for one minute outside of the threshold (Arnardottir, Koster, Van Domelen et al., 2012; Matthews, 2005). All PA variables (TPA, WT-TPA, LLPA, WT-LLPA, LSPA, WT-LSPA, MVPA, WT-MVPA, SD-TPA, SD-LLPA, SD-LSPA and SD-MVPA) and the SB variables were extracted using customized software programmed in Matlab version R2013a (The Mathworks, Inc, Natick, MA).

2.4 Statistical analyzes

SAS 9.4 was used for statistical analysis. To adjust for the skewness, PA variables were square root transformed and all parametric statistical tests were conducted on transformed data (all average numbers in texts, tables and graphs were produced from original data). For the primary analysis (two one-week free-living measurements), a mixed model ANOVA for repeated measures was used to explore the association between the accelerometer variables and age, sex, BMI, health status, temperature and day length. The standard β values were used to compare the relative strength of contributions by each variable to PA. For additional analyses, the following procedures were implemented. Due to high frequency of zeros, paired, nonparametric comparisons (Wilcoxon Signed Rank test) were used to test for seasonal difference in the number of bouts, accumulated minutes of bouted activity, and total counts accumulated in ≥5 min bouts of LSPA and ≥10 min of MVPA. Wilcoxon test was also used to compare the

accumulated min and counts between low- and high active participants. Wilcoxon test was used to compare summer to winter change between groups (sex and low vs. high active participants; group-season interaction). Results of the bouted activity are presented as lower quartile (LQ), median value (MD) and upper quartile (UQ). Low- and high active participants were separated by the median of the mean TPA for summer and winter. McNemar´s test was then used to compare summer and winter proportions of participants who had at least 1 bout of ≥5 min LSPA and ≥10 min MVPA. Chi-Square test was used to compare groups. The proportion of participants that reached the recommendation of 150 min per week (or 21.4 min per day on average) of moderate intensity PA was calculated, for both summer and winter. McNemar´s test was then used to compare summer and winter proportions.

3. Results

Demographic and Envorinmental measures

Descriptive statistics for the subpopulation of the 138 individuals who had at least 4 days of valid measurements during a week long PA measurements during both summer and winter, are displayed in Table 1. The mean age of the participants was 80.3 years with a range between 73 to 91 years (60.1% women). Self-reported health status was 2.6 ± 1.2. Also, average day length and temperature during activity measurements, as well as selelcted activity variables for the longitudinal design are shown in Table 1. During the summer, which had more daylight and higher temperature, all PA variables had higher values, except for MVPA (and WT-MVPA) and less time was spent in SB.

Predictors of Physical Activity

Results of the mixed model ANOVA are shown in Table 2. Separate models were used for each of the seasonal variables (day length and temperature) due to high colinearity. Inclusion of either seasonal variable in the models, caused differences between summer and winter in any of the PA and SB variables to become non-significant (statistical results not shown). When the day length variable was replaced by the temperature variable, the results in all covariates were very similar. Age was most strongly associated with all PA variables and with the day-to-day variation in the same variables, with β values from -0.25 to -0.44. More SB was also most strongly associated with older age (β= 0.36). There was an inverse association between BMI and all PA variables, with β values from -0.16 to -0.24, and a direct association was between SB and BMI (β= 0.18). Women had more LLPA (β= 0.16) (and WT-LLPA β= 0.16) compared to men. Self-reported health status was not associated with any of the PA variables. Cross-sectional regression analysis performed on PA and SB data from the whole sample (590 subjects) resulted in very similar beta, CI and p-values as those seen for the longitudinal seasonal variables shown in Table 2 (cross-sectional results not shown [supplementary data can be applied]).

Bouts of Physical Activity

Most of the high active participants achieved at least one ≥5 minutes bout of LSPA over all valid days, both during summer and winter, but only 58% the low active participants achieved at least one ≥5 minutes bout of LSPA over all valid days during the winter and around 78% during the summer (Table 3). The number of bouts, counts and minutes accumulated in ≥5 minutes bouts of LSPA were higher during the summer compared with winter in both low- and high active participants and there was a significant difference between the low- and high active participants. Difference between summer and winter in all above variables was significantly higher for high activity participants than for low activity participants, i.e. significant interaction (Table 3). Half of the high active participants achieved at least one ≥10 minutes bout of MVPA over all valid days, both during summer and winter, and less then 10% of the low active participants achieved at least one ≥10 minutes bout of MVPA over all valid days during both seasons (Table 4). The low active participants did not accumulate any bouts, counts, or minutes in ≥10 minutes bouts of MVPA, while those classified as high active accumulated significantly higher values for all variables (Table 4). Only 1.5% reached the recommendation of accumulating 150 min per week of PA in ≥10 min bouts of MVPA during the summer, and 4.4% during the winter. When bouts of ≥5 min of LSPA were used as a minimum of continuous PA, 26.8% accumulated 150 min per week of PA during the summer and 17.4% during the winter (Table 5).

Table 1: Demographic, environmental and activity parameters (mean and standard deviation (SD)) for sub-groupof participants with repeat visits during summer and winter.

Demographics	
N	138 (F=83; M=55)
Age, yr	80.3 (4.9)
Height, cm	167.4 (9.1)
Weight, kg	75.8 (14.5)
BMI, kg × m^{-2}	27.0 (4.5)
Self-Reported Health (1-excellent, 5-poor)	2.6 (1.2)

	Summer		**Winter**	
	Men	**Women**	**Men**	**Women**
Environmental				
Average Day Length [h:min × day^{-1}]	15:26 (2:51)	14:41 (2:38)	7:26 (2:04)	7:16 (1:55)
Average Temperature,°C	8.4 (2.3)	8.6 (2.5)	2.7 (2.5)	2.5 (2.7)
PA parameters				
Wear time [min × day^{-1}]	836 (79)	819 (74)	815 (75)	805 (67)
SD-Wear time [min × day^{-1}]	71.2 (35.5)	65.2 (29.7)	79.2 (32.2)	70.4 (31.6)
SB [h:min × day^{-1}]	10:29 (1:25)	10:07 (1:16)	10:43 (1:21)	10:13 (1:18)
WT-SB [percent of wear time]	75.4 (9.4)	74.3 (8.9)	78.9 (8.1)	76.2 (8.5)
SD-SB [h:min × day^{-1}]	1:18 (0:35)	1:08 (0:31)	1:20 (0:29)	1:10 (0:30)
TPA [x1000 counts × day^{-1}]	118 (83)	106 (60)	99 (66)	89 (46)
WT-TPA [counts × min^{-1}]	140 (98)	128 (67)	122 (83)	110 (55)
SD-TPA [x1000 counts × day^{-1}]	44 (39)	33 (21)	36 (32)	28 (21)
LLPA [h:min × day^{-1}]	2:48 (1:02)	2:58 (1:02)	2:21 (0:52)	2:48 (1:01)
WT-LLPA [percent of wear time]	19.9 (6.7)	21.6 (6.6)	17.3 (5.9)	20.8 (7.0)
SD-LLPA [h:min × day^{-1}]	0:38 (0:21)	0:35 (0:17)	0:32 (0:21)	0:35 (0:15)
LSPA [h:min × day^{-1}]	0:40 (0:37)	0:34 (0:28)	0:31 (0:27)	0:24 (0:18)
WT-LSPA [percent of wear time]	4.70 (4.46)	4.09 (3.28)	3.80 (3.42)	2.99 (2.15)
SD-LSPA [h:min × day^{-1}]	0:21 (0:18)	0:17 (0:13)	0:15 (0:14)	0:12 (0:09)
MVPA [h:min × day^{-1}]	0:09 (0:16)	0:05 (0:06)	0:09 (0:13)	0:04 (0:07)
WT-MVPA [percent of wear time]	1.07 (1.88)	0.61 (0.76)	1.07 (1.64)	0.49 (0.83)
SD-MVPA [h:min × day^{-1}]	0:07 (0:10)	0:05 (0:05)	0:06 (0:08)	0:04 (0:07)

PA= Physical activity; SB= Sedentary behaviour; TPA= Total PA; SD= Standard deviation, daily variation in each PA/SB;
WT-… = Physical activity variables normalized for wear time; LLPA= Low-light PA (100-759 counts × min^{-1}); LSPA= Lifestyle PA (≥760 counts × min^{-1});
MVPA= Moderate- to-vigorous PA (≥2020 counts × min^{-1}).

Table 2: Results of the mixed model ANOVA analysis of PA and SB parameters for subjects with repeated visits in the AGESII cohort. Covariates included age, sex, BMI, self-reported health status, day length and temperature. Data are presented as standardized β (β), 95% confidence level (95% CL) and p-value. A negative β value indicates an inverse relationship. Significant relationships ($p<0.05$) are bolded. Two separate models were run for each variable, where only one seasonal variable (temperature or daylength) was in each model; seasonal variables with higher β are marked with †. Other variables were included in both models but are shown in the table only for the model with the higher β of the seasonal variables.

Variables		Temperature/Day length			Age			Female			BMI			Health status		
		β	95%CL	p	β	95%CL	p	β	95%CL	p	β	95%CL	p	β	95%CL	p
WT-SB	Temperature	**-0.16†**	**-0.21;-0.10†**	**<0.0001†**	**0.36**	**0.21;0.50**	**<0.0001**	-0.12	-0.27;0.02	0.10	**0.18**	**0.03;0.33**	**0.02**	0.07	-0.08;0.22	0.35
	Day length	**-0.16**	**-0.21;-0.11**	**<0.0001**												
SD-WT-SB	Temperature	**0.13**	**0.04;0.22**	**0.007**												
	Day length	**0.18†**	**0.09;0.27†**	**0.0001†**	**-0.30**	**-0.43;-0.16**	**<0.0001**	-0.01	-0.15;0.12	0.85	-0.10	-0.24;0.04	0.14	-0.04	-0.18;0.09	0.53
TPA[a]	Temperature	**0.17†**	**0.11;0.22†**	**<0.0001†**	**-0.44**	**-0.58;-0.29**	**<0.0001**	-0.04	-0.18;0.10	0.60	**-0.21**	**-0.35;-0.06**	**0.005**	-0.11	-0.25;-0.03	0.13
	Day length	**0.14**	**0.09;0.19**	**<0.0001**												
WT-TPA[a]	Temperature	**0.15†**	**0.10;0.20†**	**<0.0001†**	**-0.42**	**-0.56;-0.28**	**<0.0001**	-0.02	-0.17;0.12	0.73	**-0.21**	**-0.35;-0.06**	**0.005**	-0.12	-0.26;0.03	0.11
	Day length	**0.13**	**0.07;0.18**	**<0.0001**												
SD-TPA[a]	Temperature	**0.13**	**0.05;0.20**	**0.0007**												
	Day length	**0.15†**	**0.08;0.21†**	**<0.0001†**	**-0.39**	**-0.53;-0.25**	**<0.0001**	-0.11	-0.25;0.02	0.10	**-0.21**	**-0.35;-0.07**	**0.004**	-0.10	-0.24;0.04	0.14
LLPA[a]	Temperature	**0.14**	**0.08;0.19**	**<0.0001**												
	Day length	**0.15†**	**0.10;0.21†**	**<0.0001†**	**-0.32**	**-0.47;-0.17**	**<0.0001**	**0.16**	**0.01;0.30**	**0.04**	**-0.16**	**-0.31;-0.01**	**0.04**	-0.01	-0.17;0.14	0.85
WT-LLPA[a]	Temperature	**0.11**	**0.06;0.17**	**0.0001**												
	Day length	**0.14†**	**0.08;0.19†**	**<0.0001†**	**-0.29**	**-0.44;-0.14**	**0.0002**	**0.19**	**0.04;0.34**	**0.01**	**-0.16**	**-0.31;-0.01**	**0.04**	-0.02	-0.17;0.13	0.78
SD-LLPA[a]	Temperature	0.07	-0.03;0.17	0.18												
	Day length	**0.13†**	**0.04;0.23†**	**0.007†**	**-0.25**	**-0.39;-0.12**	**0.0003**	0.04	-0.09;0.17	0.54	-0.08	-0.22;0.05	0.23	-0.001	-0.14;0.14	0.99
LSPA[a]	Temperature	**0.18†**	**0.12;0.24†**	**<0.0001†**	**-0.43**	**-0.57;-0.29**	**<0.0001**	-0.06	-0.20;0.08	0.39	**-0.17**	**-0.31;-0.02**	**0.022**	-0.13	-0.27;-0.01	0.07
	Day length	**0.15**	**0.10;0.21**	**<0.0001**												
WT-LSPA[a]	Temperature	**0.17†**	**0.11;0.23†**	**<0.0001†**	**-0.42**	**-0.56;-0.28**	**<0.0001**	-0.05	-0.19;0.09	0.47	**-0.16**	**-0.31;-0.02**	**0.025**	-0.14	-0.28;-0.01	0.06
	Day length	**0.14**	**0.08;0.20**	**<0.0001**												
SD-LSPA[a]	Temperature	**0.19†**	**0.11;0.26†**	**<0.0001†**	**-0.37**	**-0.50;-0.23**	**<0.0001**	-0.08	-0.22;0.06	0.24	**-0.19**	**-0.33;-0.05**	**0.008**	-0.13	-0.27;-0.01	0.06
	Day length	**0.18**	**0.11;0.25**	**<0.0001**												
MVPA[a]	Temperature	**0.08†**	**0.01;0.14†**	**0.027†**	**-0.33**	**-0.47;-0.19**	**<0.0001**	-0.13	-0.27;0.01	0.07	**-0.24**	**-0.39;-0.10**	**0.001**	-0.11	-0.26;0.03	0.12
	Day length	0.05	-0.02;0.11	0.151												
WT-MVPA[a]	Temperature	**0.07†**	**0.001;0.14†**	**0.048†**	**-0.32**	**-0.46;-0.18**	**<0.0001**	-0.13	-0.27;0.01	0.08	**-0.24**	**-0.39;-0.10**	**0.001**	-0.11	-0.26;-0.03	0.12
	Day length	0.04	-0.03;0.10	0.257												
SD-MVPA[a]	Temperature	**0.09†**	**0.01;0.17†**	**0.028†**	**-0.31**	**-0.45;-0.18**	**<0.0001**	-0.11	-0.25;0.02	0.10	**-0.24**	**-0.38;-0.10**	**0.001**	-0.09	-0.23;0.05	0.21
	Day length	**0.08**	**0.002;0.15**	**0.045**												

PA= Physical activity; WT-… = Physical activity variables normalized for wear time; SD= Standard deviation, day to day variation in each PA/SB variable; SB= Sedentary behavior; TPA=Total PA; LLPA=Low-light PA (100-759 counts × min^{-1}); LSPA= Lifestyle PA (≥760 counts × min^{-1}); MVPA=Moderate-to-vigorous PA (≥2020 counts × min^{-1}); *a*= Square root transformed; † = seasonal variable with higher β.

Table 3: Median value (MD) and inter quartile limits (IQL) for the means of the valid day values, for ≥5 min bouts of LSPA for sub-population of participants with repeat visits during summer and winter, presented separately for low- and high active participants. Low vs. high active participants were separated by the median of average TPA for summer and winter. Also, the proportion of participants who reached any bout of ≥5 min of LSPA.

	Low active (n=69)		High active (n=69)		p	p	p
	Winter	Summer	Winter	Summer	Season	Low/High	Interaction
Number of participants who achieved at least one bout of LSPA ≥5 min	40 (58.0%)	54 (78.4%)	69 (100%)	68 (98.6%)	**0.012** [a]	**<0.0001** [d]	**0.002** [e]
All subjects with repeated measures during summer and winter	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**			
Number of ≥5 min bouts of LSPA [day^{-1}]	0.17 (0; 0.50)	0.33 (0.14; 0.86)	1.5 (1.0; 2.43)	2.4 (1.29; 3.71)	**<0.0001** [b]	**<0.0001** [c]	**0.001** [e]
Counts accumulated in ≥5min bouts of LSPA [counts × day^{-1}]	1,033 (0; 4,238)	3,600 (867; 8,136)	18,608 (9,135; 55,740)	31,952 (17,574 ; 70,021)	**0.0005** [b]	**<0.0001** [c]	**0.035** [e]
Minutes accumulated in ≥5 min bouts of LSPA [min:s × day^{-1}]	0:50 (0; 3:26)	2:40 (0:50; 5:43)	12:43 (7:10; 26:08)	22:17 (10:06; 35:40)	**<0.0001** [b]	**<0.0001** [c]	**0.008** [e]

LSPA= Lifestyle PA (≥760 counts × min^{-1}); MD= Median value; IQL= Inter quartile limits;
a = McNemar´s test used to compare summer and winter; *b*= Wilcoxon Singed Rank test used to compare winter and summer; *c*= Wilcoxon test, low- and high active compared; *d*= Chi-Square test, low- and high active compared; *e*= Wilcoxon test of summer to winter change between low vs. high active participants (season-TPA interaction). Significant relationship is bolded.

Table 4: Median value (MD) and inter quartile limits (IQL) for the means of the valid day values, for ≥10 min bouts of MVPA for sub-population of participants with repeat visits during summer and winter, presented separately for low- and high active participants. Low vs. high active participants were separated by the median of average TPA for summer and winter. Also, the proportion of participants who reached any bout of ≥10 min of MVPA.

	Low active (n=69)		High active (n=69)		p	p	p
	Winter	Summer	Winter	Summer	Season	Low/High	Interaction
Number of participants that achieved at least one bout of MVPA ≥10 min	6 (8.7%)	6 (8.7%)	34 (49.3%)	35 (50.1%)	0.85 [a]	**<0.0001** [d]	0.84 [e]
All subjects with repeated measures during summer and winter	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**	**MD (IQL)**			
Number of ≥10 min bouts of MVPA [day^{-1}]	0 (0; 0)	0 (0; 0)	0 (0; 0.43)	0.14 (0;0.33)	0.85 [b]	**<0.0001** [c]	0.48 [e]
Counts accumulated in ≥10min bouts of MVPA [counts ×day^{-1}]	0 (0; 0)	0 (0; 0)	0 (0; 19,690)	3,377 (0; 14,105)	0.29 [b]	**<0.0001** [c]	0.78 [e]
Minutes accumulated in ≥10min bouts of MVPA [min:s × day^{-1}]	0 (0; 0)	0 (0; 0)	0 (0; 6:30)	1:34 (0; 4:30)	0.33 [b]	**<0.0001** [c]	0.59 [e]

MVPA= Moderate-to-vigorous PA (≥2020 counts × min^{-1}); MD= Median value; IQL= Inter quartile limits;
a = McNemar´s test used to compare summer and winter; *b*= Wilcoxon Singed Rank test used to compare winter and summer; *c*= Wilcoxon test, low- and high active compared; *d*= Chi-Square test, low- and high active compared; *e*= Wilcoxon test of summer to winter change between low vs. high active participants (season-TPA interaction). Significant relationship is bolded.

Table 5: Proportions of those who reached the PA recommendation of 150 min of moderate intensity PA × week^{-1} (US-Department-of-Health-and-Human-Services, 2008).

	season	proportion	p [a]
≥10 min bouts of MVPA	summer	1.5%	0.16
	winter	4.4%	
≥5 min bouts of MVPA	summer	2.9%	0.10
	winter	6.5%	
≥10 min bouts of LSPA	summer	13.0%	0.44
	winter	10.9%	
≥5 min bouts of LSPA	summer	26.8%	**0.005**
	winter	17.4%	

MVPA= Moderate-to-vigorous PA (≥2020 counts × min^{-1});
LSPA= Lifestyle PA (≥760 counts × min^{-1}).
a = McNemar´s test used to compare summer and winter.

3. Discussion

This is the first study to compare seasonal changes in free-living objectively measured PA and SB in older community-dwelling Icelanders, where there is considerable daylight variability throughout the year. The main findings of this study are that there was a significant difference in activity in the summer compared with in winter, with more PA and less SB during the summer. More day-to-day variations in PA and SB were observed during the summer. Furthermore, results revealed that age was the strongest predictor of all PA variables and of the day-to-day variation in these variables. Older age was also associated with more SB and less day-to-day SB variation. Participants accumulated more LSPA in 5 min bouts during the summer compared to winter and this difference was more in high active participants than it was in lower active participants.

Using accelerometry data, young to middle-aged adults in the UK (O'Connell, Griffiths and Clemes, 2014), women in the US (Buchowski, Choi, Majchrzak et al., 2009) and older adults in the UK (Davis, Fox, Hillsdon et al., 2011) and Japan (Yasunaga, Togo, Watanabe et al., 2008), were shown to have a seasonal difference in PA, with less time spent in PA during the winter. Step count in UK adults decreased during the winter (Clemes, Hamilton and Griffiths, 2011; Hamilton, Clemes and Griffiths, 2008) and the same was shown in a study of US adults (Tudor-Locke, Bassett, Swartz et al., 2004). Self-reported data has also shown a decrease in PA during the winter in UK adults (Uitenbroek, 1993), US adults (Matthews, Freedson, Hebert et al., 2001) and in Canadian adults (McCormack, Friedenreich, Shiell et al., 2010). This is confirmed in our results that also showed PA to be higher during the summer and with more day-to-day variation in PA.

In our study, participants spent most of their PA time in the LLPA intensity category, both during summer and winter, followed by LSPA intensity, with a maximum of only 40 minutes $\times$ day^{-1} during the summer for men and less for women. LLPA tends to be accumulated by

incidental activities, like shopping and walking at low pace (O'Connell, Griffiths and Clemes, 2014), while LSPA is accumulated by more structured activites like walking, vacuuming and cleaning (Hagstromer, Troiano, Sjostrom et al., 2010; Matthews, 2005). This distribution of activity is similar to previous accelerometry-based studies in older adults (Davis, Fox, Hillsdon et al., 2011) and younger women (Buchowski, Choi, Majchrzak et al., 2009) where less time was spent in light intensity PA during the winter. However, it is important to note that different cut-points are often used to identify light intensity PA. Davis *et al.* (Davis, Fox, Hillsdon et al., 2011) used 100-1951 counts × min^{-1} to identify light intensity PA and O´Connell *et al.* (O'Connell, Griffiths and Clemes, 2014) used 100-759 counts × min^{-1}. In the current study we use LLPA to identify the activity performed at 100-759 counts × min^{-1}; all activity ≥760 counts × min^{-1} is called LSPA.

Sedentary behavior, as a proportion of wear time, was greater during winter than summer and overall was quite high, ~75% of wear time or >10 hrs × day^{-1}. Similar sedentary time was observed in a previous study of older adults with comparable mean age (78 years) (Davis, Fox, Hillsdon et al., 2011) and in slightly older study populations (≥ 80 years) (Buman, Hekler, Haskell et al., 2010; Lohne-Seiler, Hansen, Kolle et al., 2014). Seasonal changes in SB have been observed in younger adults (Buchowski, Choi, Majchrzak et al., 2009; O'Connell, Griffiths and Clemes, 2014), but to our knowledge, this is the first accelerometer study to show SB in older adults to be affected by season.

Overall, our participants are less active than cohorts with similar mean age (Davis and Fox, 2007; Davis, Fox, Hillsdon et al., 2011). Very little time was spent in MVPA both during summer and winter. Men averaged only 9 min each day of MVPA during summer and 8 min during winter, and women averaged only 5 min during the summer and 4 min during the winter. The limited time spent in MVPA shown in our study both in summer and winter is less than has been observed in previous studies in older adults using accelerometers (Buman,

Hekler, Haskell et al., 2010; Davis and Fox, 2007; Davis, Fox, Hillsdon et al., 2011; Evenson, Buchner and Morland, 2012; Martin, Koster, Murphy et al., 2014). However, those studies used lower cut points for MVPA and had lower mean age than the current study (Davis and Fox, 2007; Davis, Fox, Hillsdon et al., 2011; Evenson, Buchner and Morland, 2012; Martin, Koster, Murphy et al., 2014).

According to the PA recommendation, aerobic PA should be performed in episodes of at least 10 min bouts of MVPA (US-Department-of-Health-and-Human-Services, 2008), but older people find it difficult to reach and maintain this intensity for longer period of time (Brawley, Rejeski and King, 2003; Burchfiel, Sharp, Curb et al., 1995; Hagstromer, Oja and Sjostrom, 2007; Hansen, Kolle, Dyrstad et al., 2012; Ortlieb, Gorzelniak, Nowak et al., 2014; Troiano, Berrigan, Dodd et al., 2008). When using MVPA bouts of 10 min as a minimum, the proportion of older adults accumulating 150 min per week of PA, is only 2.4% to 11.9% and decreases with age (Berkemeyer, Wijndaele, White et al., 2016; Lohne-Seiler, Hansen, Kolle et al., 2014; Ortlieb, Gorzelniak, Nowak et al., 2014; Troiano, Berrigan, Dodd et al., 2008; Tucker, Welk and Beyler, 2011). In the present study it is even lower, or 1.5% in the summer and 4.4% in the winter. It has been suggested by Buman *et al.* (Buman, Hekler, Haskell et al., 2010) that it may be more realistic to focus the recommendations for older individuals on replacing SB by less intense PA rather than on accumulating traditionally defined bouts of MVPA. Based on this, LSPA bouts of minimum of 5 min in duration were chosen in our study for comparison with 10 min bouts of MVPA. Using this as a minimum of continuous PA when accumulating the recommended 150 min of PA, 27% of our sample reached the target in the summer and 17% in the winter (Martin, Koster, Murphy et al., 2014; Matthews, Keadle, Sampson et al., 2013). Furthermore, our results show that half of the high active participants achieved at least one bout of ≥10 min of MVPA over all valid days measured during either summer or winter, but less then 10% of the low active participants achieved this.

When looking at LSPA, most of the high active participants achieved at least one bout of ≥5 min of LSPA, during both seasons, while it goes down to 58% in the low active participants during the winter. Thus, our results support the notion, that the minimum of 10 min bouts of MVPA when accumulating PA, may be too ambitious for many older adults. By reducing the intensity and time of the minimum bout to 5 min of LSPA, it seems to be more achievable and realistic for larger part of older adults to reach the recommendations.

Studies have shown that both younger and older adults are less active in poor weather conditions (Chan, Ryan and Tudor-Locke, 2006; Togo, Watanabe, Park et al., 2005). Cold temperatures, rain, snow and wind are frequent events in Iceland throughout the year, and they are exacerbated in the winter. Combined with darkness and slippery conditions, it is likely that outdoor PA would be challenging, especially for older populations (Kolle, Steene-Johannessen, Andersen et al., 2009; Matthews, Freedson, Hebert et al., 2001; McGinn, Evenson, Herring et al., 2007; Tucker and Gilliland, 2007). Length of daylight has been shown to have influence on the total amount of PA, but it varies between seasons and countries (Kolle, Steene-Johannessen, Andersen et al., 2009; Matthews, Freedson, Hebert et al., 2001; McGinn, Evenson, Herring et al., 2007; Salama, Noirot, Bataille et al., 2007; Sumukadas, Witham, Struthers et al., 2009; Togo, Watanabe, Park et al., 2005; Uitenbroek, 1993). During the mid-summer in Iceland, there is daylight around the clock, but during the mid-winter there are only a few hours of daylight. In our study the average difference in daylight between seasonal visits was around 7.5 hours. The change in temperature between seasons was not as dramatic, only around 6°C in mean temperature. On days with higher temperature or longer daylight, almost all types of PA were higher and more day-to-day variation was observed. Consequently, lower temperature was associated with more SB. Although the daylight difference is dramatic, the relative difference in PA (2.8-17.2%) and SB (0.4-1.2%) are relatively small in comparison. It might be speculated that the population is well adapted

to the changes in daylight. On the other hand, although temperature was found to have a similar effect size (β) to day length for predicted PA variables, the seasonal temperature variation is much smaller than that of a more continental climate.

The strength of the study is that no other study has looked at seasonal changes in an older population living at a high latitude, where the daylight change is dramatic between summer and winter months. Findings are based on the well-characterised large-population-based cohort of older Icelandic adults. The participation in the study was excellent, with 73.1% (n= 160) of subjects agreeing to participate; and the compliance was high, as 88.6% of the participants had four valid days of measurements. The use of objective measurements is also an advantage and is thought to be a better option to study free-living PA than questionnaires, which tend to overestimate PA levels and/or underestimate SB (Chinapaw, Slootmaker, Schuit et al., 2009; Tudor-Locke and Myers, 2001). There are also some limitations that need to be accounted for when interpreting the results. Accelerometers miss some movement patterns, like upper body movements during activies like heavy carrying and lifting. They are also limited in detecting non-ambulatory activities like cycling (Chen and Bassett, 2005) and water activies like swimming (Copeland and Esliger, 2009). The influence of daylight and temperature could not be separated in this specific dataset.

In conclusion, our longitudinal data show that healthy older community-dwelling Icelandic men and women were more physically active and less sedentary during the summer as compared to the winter. In studies on PA and SB in older people, it is important to consider seasonal differences during data collection and in analysis of data. As very few reach and maintain MVPA in 10 min bouts, it may be more realistic to use LSPA in 5 min bouts as a minimum when accumulating the recommended 150 min per week of PA for older adults.

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Disclosure statement

The authors have no conflicts to disclose.

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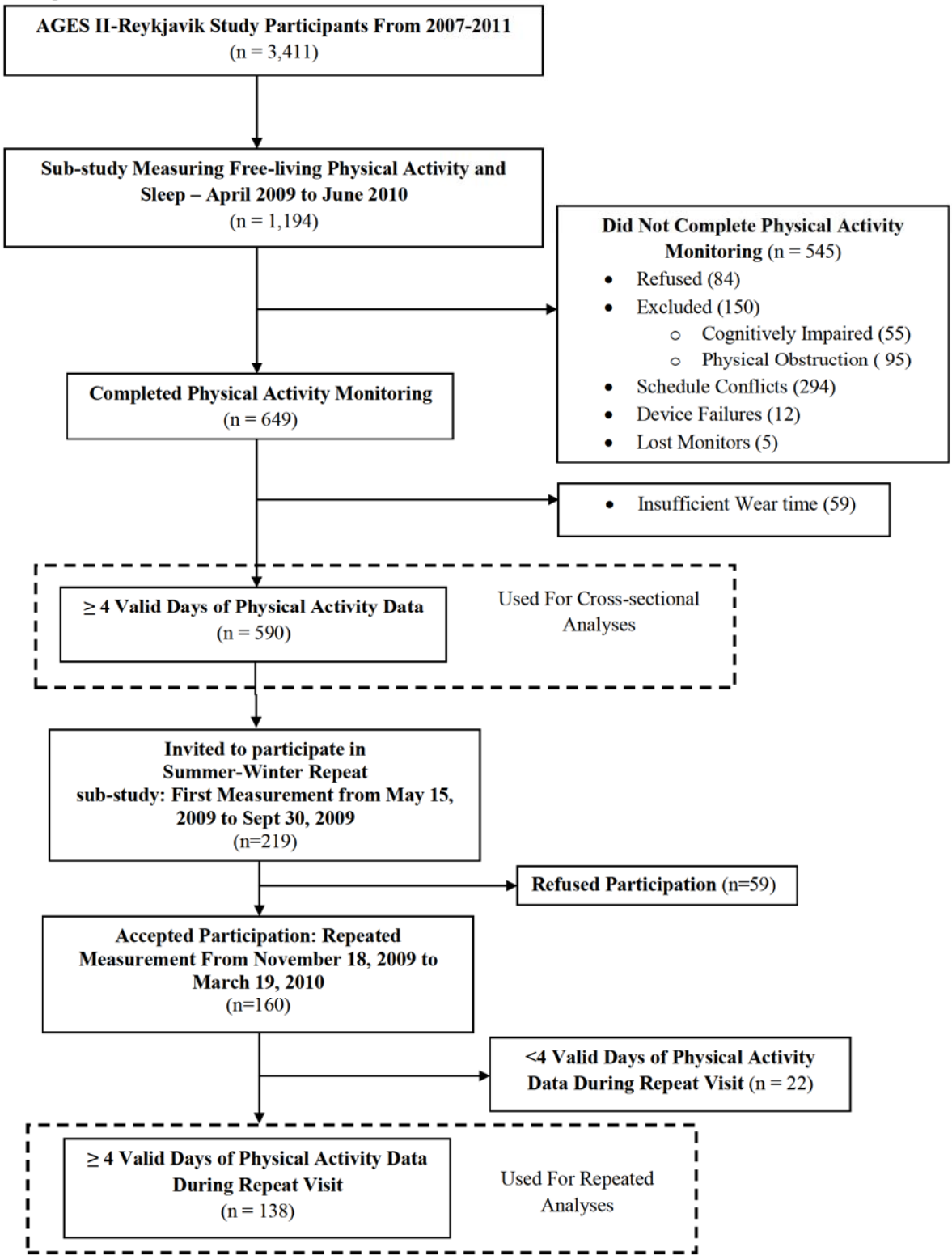
Figure 1


AGES II-Reykjavik Study Participants From 2007-2011
(n = 3,411)
Sub-study Measuring Free-living Physical Activity and Sleep – April 2009 to June 2010
(n = 1,194)
Did Not Complete Physical Activity Monitoring (n = 545)
Refused (84)
Excluded (150)
Cognitively Impaired (55)
Physical Obstruction (95)
Schedule Conflicts (294)
Device Failures (12)
Lost Monitors (5)
Completed Physical Activity Monitoring
(n = 649)
Insufficient Wear time (59)
≥ 4 Valid Days of Physical Activity Data
(n = 590)
Used For Cross-sectional Analyses
Invited to participate in Summer-Winter Repeat sub-study: First Measurement from May 15, 2009 to Sept 30, 2009
(n=219)
Refused Participation (n=59)
Accepted Participation: Repeated Measurement From November 18, 2009 to March 19, 2010
(n=160)
<4 Valid Days of Physical Activity Data During Repeat Visit (n = 22)
≥ 4 Valid Days of Physical Activity Data During Repeat Visit
(n = 138)
Used For Repeated Analyses

Paper III

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JCSM
Journal of Clinical Sleep Medicine

SCIENTIFIC INVESTIGATIONS

Influence of Day Length and Physical Activity on Sleep Patterns in Older Icelandic Men and Women

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Study Objectives: To identify cross-sectional and seasonal patterns of sleep and physical activity (PA) in community-dwelling, older Icelandic adults using accelerometers.

Design: Seven-day free-living protocol as part of a larger population-based longitudinal observational-cohort study.

Setting: Greater Reykjavik area of Iceland.

Participants: 244 (110 female), older Icelandic adults (mean age 79.7 ± 4.9 years). A subpopulation (n = 72) repeated the 7-day measurement during seasonal periods with greater (13.4 ± 1.4 h) and lesser (7.7 ± 1.8 h) daylight.

Interventions: None.

Measurements and Results: Cross-sectional analyses using multiple linear regression models revealed that day length was a significant independent predictor of sleep duration, mid-sleep, and rise time (all $p < 0.05$). However, the actual within-individual differences in sleep patterns of the repeaters were rather subtle between periods of longer and shorter day-lengths. Compared to women, men had a shorter sleep duration (462 ± 80 vs. 487 ± 68 minutes, $p = 0.008$), earlier rise time, and a greater number of awakenings per night (46.5 ± 18.3 vs. 40.2 ± 15.7, $p = 0.007$), but sleep efficiency (80.9 ± 10.1% vs. 82.2 ± 9.8%) and onset latency (34.4 ± 28.7 vs. 39.3 ± 33.6 minutes) were similar between the two sexes. Daily PA was also similar between men and women (134 ± 70 and 127 ± 62 counts/wear-time minute) and between periods of longer and shorter day-lengths (125 ± 67 and 118 ± 73 counts/wear-time minute). BMI, age, gender, and overall PA all contributed to the variations in sleep parameters using multiple regression analysis.

Conclusions: The sleep and PA characteristics of this unique population revealed some gender differences, but there was limited variation in response to significant daylight changes which may be due to long-term adaptation.

Keywords: aging, seasonal, total sleep time, physical activity, accelerometer

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INTRODUCTION

The importance of sleep to physical and metabolic health is well documented.[1,2] Although sleep needs are thought to be independent of age, older people often have more sleep problems, such as premature awakening, fragmented sleep patterns, and reduced depth of sleep.[3–5] Poor sleep quality among older adults has been associated with declines in both physical and mental function and increased risk of all-cause-mortality.[2,6–9] Thus, it is important to identify factors that may influence both the duration and the quality of sleep in older adults.

The causes for reduced sleep duration and quality in older people are not clear. There is some evidence to suggest that circadian regulation of sleep weakens with age,[3] resulting in reduced sleep consolidation and changes in sleep-wake timing.[10] However, additional factors, such as the response to various environmental cues could also play a role. For example, external environmental factors, particularly variations in artificial light exposure and day length, have been shown to influence sleep patterns and quality.[11–15] Increased exposure to artificial light has been shown to increase sleep disturbances[11] and prolong sleep onset latency in an older population.[12]

BRIEF SUMMARY

Current Knowledge/Study Rationale: Both physical activity and changes in day length are thought to influence sleep patterns, but the combined effect on older adults is not well understood. We sought to identify seasonal patterns of sleep and physical activity in a large group of community-dwelling, older Icelandic adults using objective actigraphy-based measurements.

Study Impact: Found that while day length and activity both had a significant influence on the pattern of sleep timing, the actual within-individual differences of the repeaters were rather subtle between periods of longer and shorter day-lengths. We conclude that the limited variation in sleep patterns and quality in response to significant changes in daylight may be due to long-term adaptation in this group of older Icelandic adults.

Similarly, increased light exposure in laboratory settings has been show to elicit similar circadian shifts in younger and older adult populations,[13] but older adults appear to have blunted responses to lower light levels[13] and blue light exposure.[16,17] Reduced daylight exposure due to change of season has also been shown to prolong the onset of sleep[14] and cause shifts in bed- and rise-times[14] in younger adult populations. But day length has not been shown to have a dramatic effect on the quality of sleep,[14] and observations of its influence on sleep duration have been mixed.[14,15]

It is also plausible that changes in physical activity (PA) patterns may contribute to reduced quality and duration of sleep in older adults. Increased PA is thought to lead to reduced sleep disturbances[18], but PA is known to decline with age,[19–21] and this trend may contribute to the reduced sleep quality reported by older individuals. Very few studies have simultaneously captured objectively measured sleep and PA data in older populations,[22] and little is known about the interaction of day length and physical activity on sleep patterns in older individuals.

The primary goal of this study was to delineate the potential effects of day length, objectively measured PA, and other subject characteristics on sleep quality and patterns measured by wrist actigraphy in a group of generally healthy, community-dwelling, elderly Icelandic population. Iceland is known to have one of the world's highest life expectancies—currently 82 years—as well as one of the highest healthy life expectancies, or the number of years a person can expect to live in full health, as defined by the World Health Organization (WHO).[23] Iceland's unique geographical location (latitude 64–66°North) results in a wide variation in daylight hours, 4–21 hours between winter and summer months. This large seasonal variation in daylight hours offered an ideal opportunity to study the impact of daylight length on the objectively measured sleep and PA in a population of older adults.

METHODS

Study Population

The Age, Gene/Environment Susceptibility (AGES)-Reykjavik Study was designed to assess the influence of environment, genetic factors, and gene-environment interaction on various health topics related to aging in a historically healthy, aging population with high life expectancy.[24] The study was initiated with a first wave of data collection from 2002–2006 with 5,764 participants who were recruited from the original Reykjavik Study which has collected data on age-related topics since 1967.[24] The second wave of data collection (AGESII-Reykjavik) involving 3,411 participants took place between 2007 and 2011. A sub-study involving objectively measured, free-living PA and sleep using accelerometers occurred between April 2009 and June 2010. Further details of the AGES-Reykjavik study design and assessment can be found elsewhere.[24]

From a total of 1,194 people participated in the AGESII-Reykjavik study over the period in which PA were measured, completed data was successfully collected from 654 participants, all of whom did not have cognitive impairment (Mini Mental State Examination score > 20) or physical obstructions (e.g., blindness). A flow chart for this study population is shown in **Figure 1**. A detailed analysis of the PA patterns in this population has been previously described.[25]

Two hundred sixty-three of the remaining 654 participants were given wrist-worn accelerometer for sleep assessment, due to the limited availability of the devices. The 244 participants with ≥ 4 valid days (≥ 10 h wear time)[21] of hip-worn PA data were used in the final cross-sectional analysis. Four of the subjects failed to answer a questionnaire related to health status and were excluded from any multivariate analyses which used this as a covariate. This group of subjects formed the basis for our cross-sectional data analyses to explore the between-individual differences of sleep quality and patterns, and their associations to subject characteristics, environmental factors, and PA measures.

Understanding the limitations of cross-sectional analysis, we designed a further examination to study the influence of day length on within-individual changes in patterns of sleep and PA. Thus, we asked a subsample of 72 subjects whose measurement period began between August 1, 2009, and October 1, 2009, to repeat the measurements of sleep and PA during a period with fewer daylight hours occurring between January 1, 2010, and March 18, 2010. Two hip worn PA monitor device failures occurred during the repeat measurement, leaving 70 subjects with valid sleep assessment data and at least 1 day of valid hip-worn PA data during seasonal periods of greater and lesser hours of daylight.

All participants provided informed consent and the study was approved by the Icelandic National Bioethics Committee (VSN: 00–063), the Icelandic Data Protection Authority, and the institutional review board of the US National Institute on Aging, National Institutes of Health.

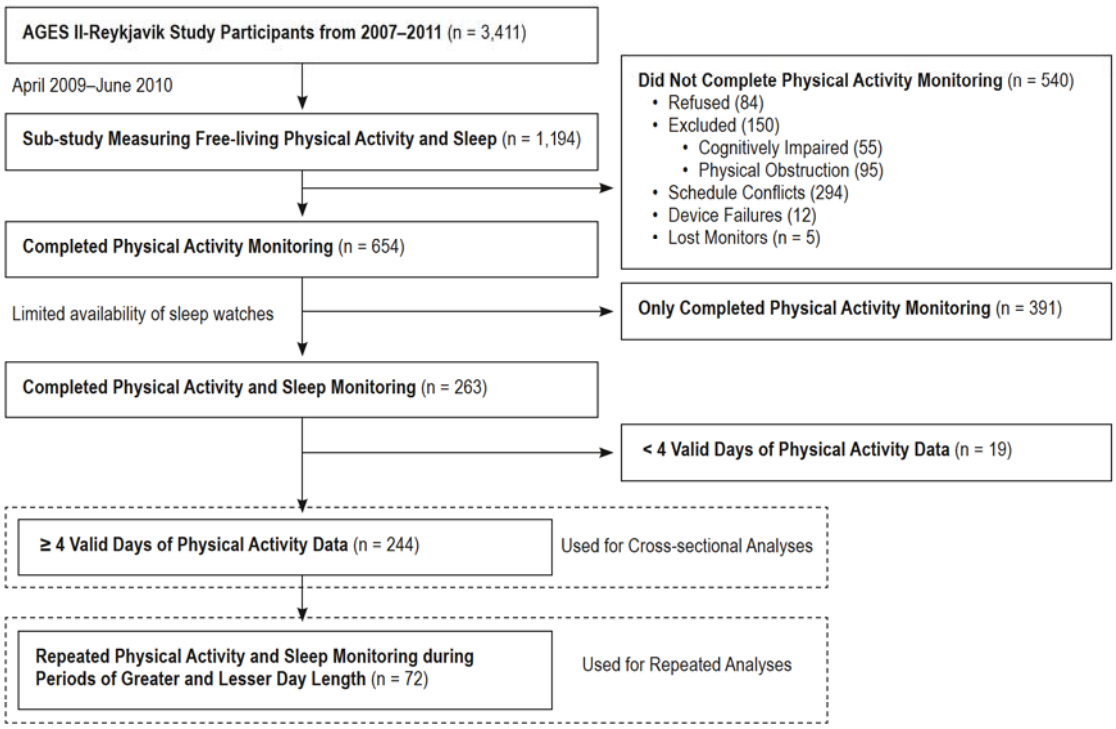
Demographic and Environmental Parameters

Participants came to the Icelandic Heart Association in Kópavogur, Iceland for assessment of cognitive and physical function as part of the AGESII-Reykjavik study. Height and weight were taken using standardized procedures and body mass index (BMI) was computed as the ratio weight/height^2 (kg/m^2). Participants reported overall health status on a discrete scale (1-excellent, 2-very good, 3-good, 4-fair, 5-poor) and whether or not they had been diagnosed with depression in the past 5 years (0-no, 1-yes, 8-not sure) as part of a comprehensive series of health history questionnaires administered to all AGESII participants.[24] Subjects were also asked to report all medication used in the two weeks prior to their visit. The hours of daylight and over each participant's week of free-living measurement were obtained using the Sunrise/Sunset calculator provided by the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html). The average daily outdoor temperature over the same period was obtained from the Weather Underground (www.wunderground.com) historical weather data.

Sleep Measurements

Participants were given actigraphy-based sleep watches (Actiwatch Spectrum, Phillips-Respironics, Bend OR) to wear on

Figure 1—Flow chart describing participants recruited from the AGES II-Reykjavik Study for cross-sectional and repeated visit analysis of sleep and activity patterns.



the non-dominant wrist for 7-day free living sleep assessment. The watches contain motion-sensitive accelerometers which have been previously validated for objective sleep measurement.[26] Each watch was programmed to record wrist-activity and white-light intensity in 15-sec epochs. Rest and sleep periods were automatically identified using the manufacturer software[27] (Actiware version 4.0) and visually inspected and compared to the hip PA monitor non-wear events and the hand-written sleep diary that each subject kept. For sleep analysis, the wake threshold of the actiwatch data was set medium (40 activity counts), sleep onset and end were both set to 10 minutes, and white light threshold was 1000 lux. The following parameters were reported for each sleep event over the 7-day period using the Actiware software[27]: bedtime (start of the rest period, time subject gets in bed), rise time (end of the rest period, time subject gets out of bed), rest duration (rise time minus bed time), sleep duration (time within the rest period that was scored as sleep), onset latency (sleep onset time minus bed time), number of awakenings during sleep period, minutes of waking after sleep onset (WASO), mid-sleep time (midpoint between bed time and rise time), and sleep efficiency (percent of rest period that participant was scored as sleep). Further, the white light intensity was averaged over each complete day and for each rest and sleep period. Fifty-three different sleep watches were used over the course of the study.

Physical Activity Measurement

Accelerometry-based PA monitors (Actigraph GT3X, Actigraph LLC, Pensacola, FL) were worn on the right hip throughout the 7-day free-living period. They were used to record PA intensity, computed as manufacturer specific activity counts in the vertical plane of motion, on a second-by-second basis and accumulated over each valid day of PA-accelerometer wear. The daily PA activity count totals provide similar PA intensity information as those found in other large epidemiologic studies of free-living PA, including the National Health and Nutrition Examination Survey (NHANES)[21] and the larger cross-sectional analysis of PA in the AGES II cohort.[25] Participants were told to remove the device before going to bed at night and before showering, bathing, or other water activities. Periods of non-wear were also automatically detected using a previously described method, 60 minutes or more of consecutive zero activity counts, allowing 1–2 minutes < 100 activity counts.[21] A technician reviewed the diary and all detected non-wear periods with each participant using customized visualization software (Matlab version 2006, The Mathworks Inc, Natick, MA). Days with < 10 h of wear-time were considered invalid.[21] Ninety-two different Actigraph accelerometers were used over the course of the study.

Statistical Methods

All descriptive data were reported in mean and standard deviation. Data were organized by a customized Matlab program,

and statistical analyses were performed using R (version 3.1.0; http://www.r-project.org/). The significance level was set at $p < 0.05$ and two-sided. Normality of each variable was checked and confirmed using Q-Q plots before analyses.

Cross-Sectional Analysis

Spearman correlations were used to identify potential relationships between sleep measures, subject demographics, and PA measures. To preserve sufficient power, only those measures achieving Spearman correlation coefficients with the significance ($p < 0.05$) were selected to enter the stepwise, multivariate regression to further explore the relationship between sleep parameters, gender, PA, and day length. Separate multiple linear regression models were evaluated using sleep duration, rest duration, sleep efficiency, onset latency, WASO, number awakenings, and sleep midpoint time as independent response variables while age, sex, BMI, self-reported health status, total activity counts per wear time minute, outdoor temperature, diagnosed depression, and day length were used as covariates in each of the regression models. The use of antidepressants, benzodiazepines, and all other sleep medications were combined into one variable and used as a covariate in the regression models. Backward-elimination regression analysis was used to identify significant, independent predictors for each of the sleep parameters listed. Covariates with significance at or below 0.10 were retained during each step of the analysis.

Within-Individual Visits

Comparisons between the environmental and physical activity variables acquired during periods of long and short day lengths were performed using paired t-tests. Linear mixed models with random intercepts were used to compare sleep parameters collected over 2 measurement periods separated by 147 ± 18 days on average. Each sleep parameter served as a response variable in separate models. Subject identification was the random effects variable in each model. Other covariates of BMI, age, gender, self-reported health status, diagnosis of depression, sleep medication usage, and day length were included as fixed effects variables in each model.

RESULTS

Cross-Sectional Analysis

Demographics

Characteristics of the study participants were presented in **Table 1**. The study population had an average age of 79.5 ± 4.8 years and BMI of 26.9 ± 4.7 kg/m². Over 70% of the participants self-reported to be in good health or better, while less than 3% of participants reported to have poor health status. The daily hours of daylight over the study period varied widely, from 4.4 h (December) to 16 h (August) and the average outdoor temperature varied from −3.1°C to 11.3°C. Over a third of the subject (38%) reported using medications known to induce sleep including antidepressants, benzodiazepines, and other sleep medications, and usage was higher in women (44%) than in men (27%). However, no relationship was found between the use of sleep medication and hours of daylight during the study.

Sleep

Patterns of sleep are presented in **Table 1**. Both men and women went to bed at around the same time (23:28 ± 61.9 min), but men arose earlier (08:15 ± 69.5 min vs. 08:51 ± 54.6 min, $p < 0.01$), leading to significantly shorter rest (529.4 ± 72.4 vs. 557.6 ± 60.4 min/night, $p < 0.01$) and sleep durations (461.7 ± 79.9 vs. 486.9 ± 68.0 min/night, $p < 0.01$). Men awoke more often during sleep than women (46.5 ± 18.3 vs. 40.2 ± 15.7 awakenings/night, $p < 0.01$). There were no gender differences in sleep efficiency, WASO, or onset latency.

Physical Activity

Cross-sectional PA data is presented in **Table 1**. Most subjects (> 85%) acquired ≥ 6 valid days of PA measurement. There were no significant differences between men and women in terms of valid days of wear, daily wear-time, daily activity counts, or counts per wear-time minute.

Predictors of Sleep Measures

The results of the backward-elimination multiple regression analyses are presented in **Table 2**. Both increases in age and in BMI were independently associated with a decrease in sleep efficiency and an increase in WASO. Age was also negatively associated with both bedtime and rise time, suggesting that, as age advances, individuals go to bed and rise earlier. The multiple regression analysis also confirmed the independent association between genders and rest and sleep duration, with men having shorter durations as a result of earlier rise times compared to women. The analysis also confirmed that men had a greater number of awakenings during the night. Sleep medication usage was found to independently predict longer rest duration and onset latency and later rise and mid-sleep times, while diagnosed depression was found to significantly predict longer sleep duration and shorter onset latency. Higher daily PA was only found to be independently associated with earlier rise times. Interestingly, length of daylight was also found to independently predict rest and sleep duration and mid-sleep and rise times. On days with greater number of daylight hours, participants tended to have significantly shorter rest durations ($\beta = -5.2$ min/daylight h) and sleep durations ($\beta = -4.1$ min/daylight h) and earlier rise times ($\beta = -3.5$ min/daylight h) and mid-sleep times ($\beta = -1.9$ min/daylight h). Additionally, models pertaining to sleep timing and duration, including the mid-sleep and rise times and rest and sleep durations, had the highest adjusted R^2 values and included both day length and gender as significant independent predictors. Neither self-reported health status nor average outdoor temperature was found to independently predict any of the sleep outcomes.

Repeated Measures in a Subgroup

Demographic and Environmental Measures

Mean results for the subpopulation of 72 individuals who repeated the week long PA and sleep measurements during

Table 1—Demographic, environmental, activity, and sleep parameter for cross-sectional population of older Icelandic adults.

	All	Men	Women	p
n	244	110	134	
Demographic and environmental				
Age (y)	79.5 ± 4.8 (73.0–91.0)	79.7 ± 4.6 (74.0–91.0)	79.4 ± 4.9 (73.0–91.0)	0.65
Height (cm)	167.9 ± 9.4 (149.0–194.0)	175.9 ± 6.4 (160.0–194.0)	161.3 ± 5.6 (149.0–180.0)	< 0.01
Weight (kg)	76.2 ± 16.0 (42–120)	82.7 ± 15.7 (54.0–120.0)	70.9 ± 14.3 (42.0–118.0)	< 0.01
BMI (kg/m^2)	26.9 ± 4.7 (15.6–42.8)	26.7 ± 4.4 (17.2–37.8)	27.2 ± 5 (15.6–42.8)	0.39
Self-reported health (1 excellent, 5 poor)*	2.6 ± 1.2 (1.0–5.0)	2.5 ± 1.2 (1.0–5.0)	2.7 ± 1.2 (1.0–5.0)	0.13
Anti-depressant usage (%)	11.1	10.0	11.9	0.63
Benzodiazepine usage (%)	11.9	9.1	14.2	0.22
Other sleep medication usage (%)	24.2	15.5	31.3	< 0.01
All sleep medication/anti-depressant usage (%)	37.7	27.3	43.6	< 0.01
Diagnosed depression (%)*	4.60	3.80	5.30	0.6
Daylight, h	10.3 ± 3.1 (4.4–16)	10.3 ± 3.0 (4.6–15.9)	10.3 ± 3.2 (4.4–16.0)	0.97
Outdoor temperature (°C)	4.9 ± 3.5 (−3.1–11.3)	4.5 ± 3.6 (−3.1–11.3)	5.2 ± 3.4 (−2.3–11.3)	0.09
Daily average white light exposure (lux)	158.9 ± 177.7 (3.4–984.5)	165.2 ± 182.6 (3.4–984.5)	153.8 ± 174.2 (3.7–826.8)	0.62
Rest time white light exposure (lux)	23.3 ± 45.9 (0.0–303.4)	21.1 ± 41.5 (0.0–220.8)	25.1 ± 49.4 (0.0–303.4)	0.50
Sleep time white light exposure (lux)	21.0 ± 45.6 (0.0–300.4)	19.0 ± 41.2 (0.0–220.1)	22.6 ± 49.0 (0.0–300.4)	0.55
Activity measures				
Valid days of wear (> 10 h, n)	6.3 ± 0.9 (4–7)	6.4 ± 0.9 (4.0–7.0)	6.3 ± 0.9 (4.0–7.0)	0.57
Wear time (min)	830.2 ± 94.1 (641.5–1343.4)	835.2 ± 95.6 (645.5–1212.5)	826.1 ± 93.0 (641.5–1343.4)	0.45
Total counts (1000*counts/day)	109.0 ± 56.3 (14.2–349.7)	112.5 ± 58.5 (14.2–349.7)	106.1 ± 54.5 (19.5–288.2)	0.38
Wear time counts (counts/wear time min)	130.7 ± 65.1 (21.1–453.1)	133.9 ± 69.6 (21.1–453.1)	127.2 ± 61.9 (27.1–319.9)	0.43
Sleep measures				
Sleep intervals (n)	7.0 ± 0.5 (5.0–12.0)	7.1 ± 0.7 (5.0–12.0)	7.0 ± 0.4 (6.0–10.0)	0.22
Rest duration (min)	544.9 ± 67.4 (276.4–764.4)	529.4 ± 72.4 (276.4–764.4)	557.6 ± 60.4 (416.3–740.3)	< 0.01
Sleep duration (min)	475.5 ± 74.5 (190.7–741.8)	461.7 ± 79.9 (210.0–741.8)	486.9 ± 68 (190.7–662.1)	< 0.01
Onset latency (min)	37.1 ± 31.5 (1.2–208.2)	34.4 ± 28.7 (1.3–157.6)	39.3 ± 33.6 (1.2–208.2)	0.18
Sleep efficiency (%)	81.6 ± 9.9 (36.5–99.2)	80.9 ± 10.1 (48.0–99.2)	82.2 ± 9.8 (36.5–97.2)	0.34
Waking after sleep onset (WASO) (min)	31.3 ± 17.3 (0.9–148.9)	33.0 ± 20.4 (0.9–148.9)	30.0 ± 14.3 (8.8–95.6)	0.18
Number of awakenings (n)	43.1 ± 17.2 (1.0–104.0)	46.5 ± 18.3 (1.0–104.0)	40.2 ± 15.7 (10.7–89.4)	< 0.01
Bed time (hh:mm ± min)	23:28 ± 61.9 (19:49–03:49)	23:23 ± 55.9 (20:15–01:44)	23:33 ± 66.3 (19:49–03:49)	0.24
Rise time (hh:mm ± min)	08:35 ± 64.2 (05:11–11:51)	08:15 ± 69.5 (05:11–10:45)	08:51 ± 54.6 (05:59–11:51)	< 0.01
Mid-sleep time (hh:mm ± min)	04:43 ± 34.2 (03:12–07:17)	04:33 ± 34.1 (03:12–06:22)	4:51 ± 31.9 (03:35–07:17)	< 0.01

Data are presented as mean ± standard deviation (range) or percentage of participants. *n = 240 (All), 107 (Men), 133 (Women) for self-reported health status and diagnosed depression.

periods of longer (13.4 ± 1.4 h) and shorter day length (7.7 ± 1.8 h, $p < 0.001$) are displayed in **Table 3**. Sleep watch light sensor data indicated that participants were exposed to a greater daily amount of white light during periods of longer day length compared to those with shorter day length (221.0 ± 189.5 vs. 82.3 ± 84.8 lux, respectively, $p < 0.001$). However, there were no differences in the white light exposure recorded by the Actiwatches during rest or sleep time between the 2 measurement periods.

Physical Activity

When days were longer, participants had higher total PA counts (103,781 ± 58,777 vs. 95,152 ± 59,786 counts, $p < 0.05$) but also trended toward longer device wear-times (815.2 ± 79.4 vs. 802.7 ± 67.2 min, $p = 0.06$). Consequently, there was no difference between periods of longer and shorter day lengths when PA was normalized for wear-time (125.6 ± 69.0 vs. 117.8 ± 73.1 counts/wear-time min, respectively, $p = 0.14$).

Sleep

Results of the linear mixed effects model performed on the repeat subpopulation are summarized in **Table 4**. After controlling for demographic variables and environmental conditions in the linear mixed model, participants with repeat visits tended to rise earlier in summer months ($\beta = -3.8$ min/daylight hour, $p < 0.01$) but go to bed at approximately the same time ($p > 0.05$), leading to a shift toward earlier mid-sleep times ($\beta = -2.2$ min/daylight hour, $p < 0.01$) and a reduced rest duration ($\beta = -3.4$ min/daylight hour, $p < 0.05$). Sleep duration, sleep efficiency, sleep onset latency, WASO, and number of awakes were not found to vary significantly with hours of daylight. Similar to the cross-sectional results, gender also had a

Table 2—Results of backward-elimination, multiple regression analysis of cross-sectional sleep parameters for AGES II cohort.

		Covariates†											
		Day Length		BMI		Female		Age		Activity		Sleep Meds		Depression	
Sleep Parameters*	Adj. R^2	Std. β	p	Std. β	p	Std. β	p	Std. β	p	Std. β	p	Std. β	p	Std. β	p
Rest duration	0.147	−0.24	< 0.01	–	–	0.17	< 0.01	–	–	–	–	0.23	< 0.01	–	–
Sleep duration	0.070	−0.17	< 0.01	–	–	0.18	< 0.01	–	–	–	–	–	–	0.13	0.04
Onset latency	0.042	−0.12	0.06	–	–	–	–	–	–	–	–	0.18	< 0.01	−0.14	0.03
Sleep efficiency	0.021	–	–	−0.14	0.04	–	–	−0.14	0.04	–	–	–	–	–	–
WASO	0.047	–	–	0.19	< 0.01	–	–	0.18	< 0.01	–	–	–	–	–	–
Number of awakenings	0.027	–	–	–	–	−0.18	0.03	–	–	–	–	–	–	–	–
Bed time	0.024	–	–	–	–	–	–	−0.17	< 0.01	–	–	–	–	–	–
Mid-sleep time	0.139	−0.17	< 0.01	–	–	0.24	< 0.01	–	–	–	–	0.21	< 0.01	–	–
Rise time	0.136	−0.17	< 0.01	–	–	0.25	< 0.01	−0.13	0.04	−0.14	0.02	–	–	0.11	0.08

Separate models were used to evaluate each sleep parameter. Covariates included BMI, self-reported health status, gender, age, outdoor temperature, day length, sleep medication usage, diagnosed depression, and PA (activity counts/wear time). Data are presented as standardized Beta and p value. A negative standardized Beta value indicates an inverse relationship. *All models were adequately fit ($p < 0.05$). †Outdoor temperature and health status were not significant independent predictors of any sleep parameters tested and are not shown in the table.

significant, independent influence on sleep with women having longer onset latency ($\beta = 16.7$ min, $p < 0.05$) and later rise ($\beta = 46.3$ min, $p < 0.01$) and mid-sleep times ($\beta = 18.9$ min, $p < 0.05$) than men. Participants who used sleep medications were found to have a significantly longer rest duration ($\beta = 38.8$ min, $p < 0.05$) and later mid-sleep time ($\beta = 23.1$ min, $p < 0.05$). Physical activity was also found to have a small, but significant impact onset latency ($\beta = 0.11$ min/wear-time count, $p < 0.05$) and bed time ($\beta = -0.18$ min/wear-time count, $p < 0.05$). None of the other covariates such as age, BMI, health status, and diagnosed depression, were found to influence sleep patterns or quality in the repeat subpopulation. Outdoor temperature was excluded as a covariate due to co-linearity with day length; however results did not change appreciably when it was included.

DISCUSSION

To our knowledge, this is the first study that used objective measurements of sleep and physical activity in a group of free-living older men and women in a region where there is considerable daylight variability throughout the year. We observed that this healthy Icelandic older population slept about 8 hours per night, with around 80% efficiency, and approximately 43 awakenings per night. We also found that, on average, men rose about 35 minutes earlier than women, although bedtimes were similar across sexes (around 23:30), resulting in a significantly shorter sleep duration for men ($p < 0.01$). The cross-sectional analyses revealed some associations between sleep parameters and age, gender, BMI, PA levels, sleep medication use, and length of daylight. Using a subpopulation of 72 participants who repeated the measurements during months with longer and shorter days, we were able to confirm the cross-sectional finding that participants rose later in winter resulting in a longer time spent in bed.

In other studies where objective sleep monitors were used in generally healthy, older, free living populations, Blackwell, et al. reported similar sleep efficiency (78.1% ± 12.0%) in about 3,000 community-dwelling men (76 ± 6 years, 90% Caucasian) in the US (6 sites).[28] However, the total sleep time as measured by actigraphy was only 6.4 ± 1.2 hours in their sample, which is more than one hour less than the 7.7 ± 1.3 hours that we measured in Icelandic men. The WASO time in their study was 78.4 ± 44.3 min, more than double the 33.0 ± 20.4 min found in our study. In studies focusing on older women, Spira et al. found the total sleep time was 409.2 ± 66.0 min (6.8 ± 1.1 h), sleep efficiency of 79.9% ± 9.9%, and WASO of 65.9 ± 40.4 min in over 800 women with an average age of 82.4 years living at their own homes in the US (4 different sites).[8] Again, the Icelandic older women appeared to have longer total sleep times (487 ± 68 min or 8.1 ± 1.1 h) and about half of the WASO (30.0 ± 14.3 min). With differences between our Icelandic older population and the US studies being quite large, we could not discount the fact that both US studies used a different wrist-worn actigraphy sleep watch (Sleepwatch-O by Ambulatory Monitoring Inc., Ardsley NY) than ours (Actiwatch Spectrum by Respironics). Weiss et al. performed a validation study comparing the Sleepwatch and Actiwatch simultaneous in a group of 30 adolescent participants and found near equivalent detections of total sleep time and sleep efficiency with significant correlation coefficient values.[29] However, while the Blackwell and Spira studies used the proportional integration mode (PIM) for the Sleepwatch-O sleep/wake scoring given its higher correlation to polysomnography measurements in older adults,[30] Weiss used the time-above-threshold (TAT) algorithm. In a more recent study, Lambiase et al. (2014) used an Actiwatch-64m (also by Respironics) which uses the same accelerometer sensor and same data analysis software (Actiware), and found the total sleeping time in 121 healthy women (73.3 ± 1.7 years) in Pittsburgh PA to be 397 ± 53 min.[22] This is closer to the previous US study, conducted by Spira[8] than to our current results in Iceland, but the authors did not specify

Table 3—Demographic, environmental, activity, and sleep parameters for sub-population of participants with repeat visits during periods of longer and shorter day length.

Demographics at first visit			
n	72 (26 M, 46 F)		
Age (y)	80.1 ± 5.1 (73–94)		
Height (cm)	166.8 ± 8.5 (149.0–189.0)		
Weight (kg)	74.9 ± 14.4 (44.0–115.0)		
BMI (kg/m^2)	27.0 ± 5.0 (17.0–42.8)		
Self-reported health (1 excellent, 5 poor)	2.6 ± 1.2 (1.0–5.0)		
Antidepressant usage (%)	13.9		
Benzodiazepine usage (%)	18.1		
Other sleep medication usage (%)	25.0		
All sleep medication/antidepressant usage (%)	43.1		
Diagnosed depression (%)	5.6		
	Summer	**Winter**	**p**
Environmental			
Day length (h)	13.4 ± 1.4 (9.9–15.9)	7.7 ± 1.8 (4.9–11.3)	< 0.001
Outdoor temperature (°C)	7.9 ± 2.7 (1.9–11.3)	2.3 ± 2.7 (−3.4–6.1)	< 0.001
Daily average white light exposure (lux)	221.0 ± 189.5 (16.2–826.8)	82.3 ± 84.8 (2.5–514.2)	< 0.001
Rest time white light exposure (lux)	27.8 ± 43.7 (0.2–210.5)	28.7 ± 55.6 (0.1–227.0)	0.91
Sleep time white light exposure (lux)	24.7 ± 43.3 (0.1–210.5)	26.5 ± 54.7 (0.0–222.3)	0.82
Activity measures*			
Valid days of wear (> 10 h, n)	6.3 ± 0.9 (4.0–7.0)	6.4 ± 0.9 (4.0–7.0)	0.57
Wear time (min)	815.2 ± 79.4 (681.3–1041.0)	802.7 ± 67.2 (663.3–1022.0)	0.06
Total counts (1000*counts/day)	103.8 ± 58.8 (17.9–349.7)	95.2 ± 59.8 (16.3–30.8)	< 0.05
Wear time counts (counts/wear time min)	125.6 ± 69.0 (24.1–453.1)	117.8 ± 73.1 (22.2–401.5)	0.14
Sleep measures			
Rest duration (min)†	539.0 ± 72.0 (371.6–687.2)	554.8 ± 69.6 (330.9–689.0)	
Sleep duration (min)	464.8 ± 78.9 (190.7–642.4)	473.8 ± 66.3 (301.8–635.3)	
Onset latency (min)	39.5 ± 34.1 (4.4–208.2)	45.2 ± 34.6 (3.7–155.3)	
Sleep efficiency (%)	80.4 ± 10.1 (36.5–91.8)	79.3 ± 8.5 (56.8–93.8)	
Waking after sleep onset (WASO) (min)	32.1 ± 15.5 (7.3–99.4)	35.7 ± 20.4 (9.3–116.6)	
Number of awakenings (n)	45.5 ± 17.2 (13.0–104.0)	47.3 ± 8.4 (16.4–125.1)	
Bed time (hh:mm ± min)	23:34 ± 68.7 (20:15–03:49)	23:39 ± 77.3 (20:52–05:16)	
Rise time (hh:mm ± min)†	08:34 ± 67.9 (05:11–11:51)	08:55 ± 62.4 (06:08–10:47)	
Mid-sleep time (hh:mm ± min)†	04:44 ± 39.1 (03:12–07:17)	04:57 ± 37.8 (03:45–08:01)	

Data are presented as mean ± standard deviation (range) or percentage of participants. *n = 70 (25 M, 45 F) for Activity measures; †Sleep measures found to vary significantly with day length using linear mixed model analysis.

the sleep/wake detection parameters which may have influenced the results. Our results suggest that the total sleep time in these healthy, older Icelandic men and women were more than one hour longer than the US older people. Although sleep parameter definitions seem to be similar in all cases (e.g. total sleep time, WASO), it is still unclear what influence the monitor choice and various sleep detection algorithms may have had on these findings To the best of our knowledge, no similar data exist from other countries and regions to which we could further compare.

Another factor to consider in the interpretation of the results is the difference in the use of sleep medications amongst the populations studied. Over a third (38%) of the Icelandic participants studied reported using either a sleep-inducing medication or antidepressant (including 11% antidepressant use, 12% benzodiazepine use, and 24% other sleep medication use), which is a high percentage compared to the other studies mentioned (Lambiase[22] reported 9% using sleep medication; Spira[8] reported 7% antidepressant use and 4.8% benzodiazepine use; Blackwell[28] reported 7.9% antidepressant use, 4.5% benzodiazepine use, and 2.0% other sleep medication use). The participants in our study who reported use of these medications had longer sleep duration (488 ± 71 min with sleep medication vs. 468 ± 76 min without, $p < 0.05$), with a similar bedtime but a later rise time (08:50 vs. 08:27, $p < 0.01$) than participants who did not use sleep medication. Consequently, the high prevalence of sleep medication use may have contributed to the long sleep duration seen in this cohort. However,

Table 4—Results of a linear mixed models regression analysis of sleep parameters for the sub-population of participants with repeat visits during periods of longer and shorter day length.

			Fixed Effects Covariates†											
			Day Length			Female			Activity			Sleep Meds		
Sleep Parameters*	Marg. R^2	Cond. R^2	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Rest duration	0.16	0.70	**−3.37**	**1.10**	**< 0.01**	14.92	16.05	0.36	0.15	0.10	0.14	**38.77**	**16.36**	**0.02**
Onset latency	0.10	0.54	−1.25	0.66	0.06	**16.71**	**7.70**	**0.03**	**0.11**	**0.05**	**0.04**	5.82	7.88	0.46
Bed time	0.08	0.88	−0.38	0.73	0.61	30.69	18.50	0.10	**−0.18**	**0.09**	**0.04**	−18.35	18.66	0.33
Mid-sleep time	0.23	0.82	**−2.22**	**0.48**	**< 0.01**	**18.94**	**8.75**	**0.03**	0.04	0.05	0.38	**23.09**	**8.88**	**0.01**
Rise time	0.20	0.80	**−3.79**	**0.84**	**< 0.01**	**46.29**	**14.95**	**< 0.01**	0.004	0.09	0.96	21.28	15.18	0.17

Separate models were used to evaluate each sleep parameter. Fixed effects covariates included BMI, self-reported health status, gender, age, day length, sleep medication usage, diagnosed depression, and physical activity (activity counts/wear time). The subject identifier was used as the random effects variable. Data are presented as Beta, standard error (SE) and p value for significant fixed effects covariates. The marginal R^2 (Marg. R^2) is the variance explained by fixed effects alone; the conditional R^2 (Cond. R^2) is the variance explained by both fixed and random effects. A negative Beta value indicates an inverse relationship; significant relationships ($p < 0.05$) are bolded. *Results for sleep parameters with no significant predictors (sleep duration, sleep efficiency, number of awakenings, and wake after sleep onset) are not presented. †Body mass index (BMI), health status, age, and diagnosed depression status were not significant independent predictors of any sleep parameters tested and are not shown in the table. Outdoor temperature was excluded as a covariate due to co-linearity with day length; however results did not change appreciably when it was included.

the average sleep duration in those participants not taking sleep medication (468 ± 76 min) was still longer than those reported in other studies. Additionally, sleep medication use had little influence on the measured quality of sleep, as users and non-users did not differ in sleep efficiency, number of awakenings, or WASO. When sleep medication use was included as a covariate in the multiple linear regression analysis of the cross-sectional data, it was found to be a significant predictor of rest duration, onset latency, and rise time but had little influence on the contribution of the other independent predictors of sleep patterns and quality, such as day length, gender, age, or PA.

If this was indeed a healthier study population than those from the US, the PA measured by the hip-worn accelerometer on the Icelandic women (127 ± 62 ct/min/day) contradictorily appeared to be much less than that measured from the group studied by Lambiase[22] from the Healthy Women Study (HWS) cohort in Pittsburgh, PA, USA,[31] where the average daily activity was reported to be 190 ct/min/day. One explanation for this PA discrepancy is the difference in the age of the subjects. The women enrolled in the Pittsburgh HWS were on average about 6 years younger than those in the current study, and age-related declines in PA have been documented in similar older populations.[32,33] However, in a similar study of older adults living in urban areas in the UK with a closer mean age to the participants in our study (77.7 ± 5.8 years for men and 78.6 ± 5.7 years for women), Davis[33] also reported higher daily wear-time activity counts than those observed in our population (198 ± 117 vs. 134 ± 70 ct/min/day for men and 163 ± 116 ct/min/day vs. 127 ± 62 ct/min/day for women). Other factors that may influence the reported physical activity may be the activity monitor type and the data processing methods used in each of the studies; however, the older Actigraph GT1M monitor used in both the Lambiase[22] and Davis[33] studies has been shown to be comparable to the newer GT3X monitors used in the current study.[34] Each of the studies used different methods to determine monitor wear-time, which may have a small impact on the results. However, the wear time reported by Davis[33] (13.9 h for women and 14.4 h for men) was similar to what we have reported (13.8 h for women and 13.9 h for men); wear time in the Lambiase study[22] was not reported. It is possible that subjects in our Icelandic cohort achieved more activity than the other groups during non-wear periods by performing water sports such as swimming, given that roughly one-quarter of the AGES cohort who received an accelerometer reported swimming for exercise both in summer and winter[25]; however, we do not have sufficient information from other studies to confirm this conjecture.

We also found that total hours of daylight were statistically significantly related to sleep timing and duration but were not associated with sleep quality or physical activity patterns. Specifically, shorter days were associated with the later mid-sleep and rise times leading to longer rest and sleep durations in both the cross-sectional analysis of 244 participants and in the 72 participant subgroup which repeated the week long sleep assessments. However, the absolute sleep duration differences between the two measurement periods were only about 20 minutes (4.3 min/daylight hour). Furthermore, no differences were observed in the total sleep time, WASO, sleep efficiency, or wear-time PA level during the winter, suggesting that the older population studied here is able to adapt sleeping and physical activity patterns to accommodate the change in daylight across seasons. In fact, the comparable Actiwatch Spectrum white-light sensor readings during sleep- or rest-time between darker and lighter months seem to support this rationale (**Table 3**). However, data from the light sensor should be interpreted with caution, however, since the sensor may have become obstructed by heavy blankets or clothing[35] and the variability of light sensor measurements between devices has been shown to be significant[36] and they were not calibrated prior to use, as in other studies using the Spectrum.[37] Further, due to device memory and data use constraints, we were limited to collecting broad spectrum white light rather than the red, green, and blue spectral components which may have been helpful in differentiating the contributions of natural and

artificial light sources to the daily patterns of light exposure.[38] It has also been shown that, after a bout of increased light exposure, older adults have a diminished cognitive response,[16] reduced subjective changes in alertness and sleepiness,[17] an absence of increased PER2 clock-gene expression,[39] and reduced circadian responsiveness[13] as compared to younger subjects. These blunted responses in older subjects may be due to reduced corneal light exposure as a result of changes in pupil size[40] and lens opacity[13] that occur with advancing age, which may also help explain the small seasonal differences in sleep patterns observed in this study.

We cannot rule out the idea that the seasonal difference may be due to a difference in the outdoor temperature or precipitation rather than the difference in daylight hours, as the difference in outdoor temperature was found to differ significantly between the two study visits. However, when outdoor temperature was included as a covariate in the cross-sectional regression model and the repeat participant mixed model analysis it was not found to independently predict any of the sleep parameters. Also, the variation in outdoor temperature and precipitation from summer to winter in Reykjavik, Iceland is known to be slight relative to other locations of similar latitude. For instance, the variation in temperature in Reykjavik (average winter month low of −3°C and average summer month high of 13.3°C, a range of 16.3°C) is closer to that of San Francisco (37.8°N with a low of 7.6°C to a high of 21.2°C high, range of 13.6°C, one of the lowest in the continental US) than to Stockholm, Sweden (59°N, −5°C low to 22°C high, a 27°C difference).[41]

Our findings regarding sleep patterns and the length of daylight was similar to a Norwegian population study conducted by Sivertsen,[42] where the latitude was equal to that of Iceland. In that population study of over 43,000 participants, their self-reported time in bed was not related to the length of daylight (or month). Conversely, a self-report study conducted by Friborg[14] examined summer and winter sleep patterns in 150 Norwegian (69°N) and 180 Ghanese (5°N) men and women and found that the Norwegians rose 32 min later, had longer onset latency, and slightly reduced sleep efficiency but no change in total sleep time in winter, while sleep patterns of the Ghanese were unchanged from winter to summer. The results of the Friborg study, as well as our own, reflect some of the shifts in circadian profile found in laboratory-based light exposure studies.[13] It is worth mentioning, however, the average age of the study participants in the Sivertsen[42] study was 44.6 years and in the Friborg[14] study was 25.4 years for the Ghanese and 22.7 years for Norweigans, and we could not ascertain any subgroups that have a comparable age to our subjects (about 80 years). Additionally our assessments of free-living sleep patterns and quality used an objective monitor, which often differ from subjective self-reports.[43–45]

One of the strengths of the current study was the inclusion of a generally healthy population of older men and women living in Iceland who were part of a longitudinal study which included detailed assessments of their health status over the past 45 years. Additionally, we were able to simultaneously measure one week of free-living sleep and PA using objective wrist- and hip-worn accelerometers, respectively, with high compliance rate (nearly 100% with 6+ days of sleep and 79% with 6+ days for PA). Concordant measurement of objective sleep and hip-worn PA is rare, particularly in older populations.[22] And, unlike previous studies, we were able to compare the sleep patterns and qualities between men and women, and explore multiple factors that are thought to influence sleep. Due to Iceland's unique geographical location, which provided a relatively large variation in daylight, we were able to investigate the relationship between day length and free-living sleep-patterns in older adults more extensively. We were also able to use within-individual comparisons of sleep and PA patterns gained by repeating measurements in an opposite daylight condition to confirm cross-sectional findings that season had a statistically significant, although practically minor impact on sleep patterns and quality in this population.

A limitation of the current study is that while age, gender, length of daylight, BMI, and PA levels were independently associated with cross-sectional differences in sleep patterns (bed time, rise time, rest and sleep durations) and sleep quality (total sleep time, efficiency, WASO, and number of awakenings), we could not state with certainty that any causal relationships exist. Studying a mostly healthy population may have limited our ability to draw conclusions that relate health status to sleep patterns and it does not permit us to investigate other important relationships between sleep and health in patients with clinical conditions common to older individuals. Thus, the question of whether sleep patterns and quality impact future health remains to be answered with further follow-up in this cohort and in future studies that are designed to address these questions. Moreover, the cohort that we studied consisted of subjects between 73 and 91 years of age. The older age and healthy status could partly explain the longer sleep time and limited influence by outdoor daylight variations. The usage of sleep medication was high in the Icelandic population we studied and, along with the health status, was assessed using self-report during the participants' first visit. Therefore, it is not known whether the participants changed medication usage, or health status, between visits. However, in the cross-sectional sample, neither sleep medication use nor health status was related to day length, suggesting that it may be consistent throughout the year. Additionally, subjects who repeated the one-week measurements did not necessarily wear the same sleep-watch or hip-worn PA monitor, due to logistical limitations. This may have contributed to some variability in sleep, PA, and light measurements across study periods. Lastly, we only analyzed the night sleeping patterns and excluded naps.

In conclusion, our study of objectively measured free-living sleep and physical activity in older Icelandic men and women revealed that this population had a relatively long sleep time (about 8 h in women, and 7.7 h for men), lower average nightly awakenings, but higher use of sleep medications than most previous reports from similarly older populations. Age and BMI were found to have the greatest association with the quality of sleep and men were found to rise earlier and sleep fewer minutes per night than women. The statistically significant but small changes in sleep patterns and quality observed during periods of disparate daylight length suggest that this population is well adapted to the seasonal variation of daylight in Iceland.

ABBREVIATIONS

AGES, age, gene/environment susceptibility study
BMI, body mass index
HWS, Healthy Women Study
PA, physical activity
PIM, proportional integration mode
TAT, time-above-threshold
WASO, wake after sleep onset
WHO, World Health Organization

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Research report

Association of change in brain structure to objectively measured physical activity and sedentary behavior in older adults: Age, Gene/Environment Susceptibility-Reykjavik Study

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HIGHLIGHTS

- Accelerometer was used to measure physical activity and sedentary behavior at follow up.
- Gray matter and white matter was measured both at baseline and follow up, with 5-year interval.
- An association was found between brain atrophy and physical activity.
- There was also an association between brain atrophy and sedentary behavior, independent of lifestyle physical activity.

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ABSTRACT

Many studies have examined the hypothesis that greater participation in physical activity (PA) is associated with less brain atrophy. Here we examine, in a sub-sample ($n = 352$, mean age 79.1 years) of the Age, Gene/Environment Susceptibility-Reykjavik Study cohort, the association of the baseline and 5-year change in magnetic resonance imaging (MRI)-derived volumes of gray matter (GM) and white matter (WM) to active and sedentary behavior (SB) measured at the end of the 5-year period by a hip-worn accelerometer for seven consecutive days. More GM ($\beta = 0.11$; $p = 0.044$) and WM ($\beta = 0.11$; $p = 0.030$) at baseline was associated with more total physical activity (TPA). Also, when adjusting for baseline values, the 5-year change in GM ($\beta = 0.14$; $p = 0.0037$) and WM ($\beta = 0.11$; $p = 0.030$) was associated with TPA. The 5-year change in WM was associated with SB ($\beta = -0.11$; $p = 0.0007$). These data suggest that objectively measured PA and SB late in life are associated with current and prior cross-sectional measures of brain atrophy, and that change over time is associated with PA and SB in expected directions.

Abbreviation: AGES-Reykjavik study, Age, Gene/Environment Susceptibility Reykjavik Study; AGESII-Reykjavik study, Age, Gene/Environment Susceptibility Reykjavik Study, second phase; BMI, body max index; CSF, cerebral spinal fluid; DP, diastolic pressure; GM, gray matter; ICV, intra-cranial volume; MAP, mean arterial pressure; MRI, magnetic resonance imaging; SB, sedentary behavior; SP, systolic pressure; SPA, self-reported PA questionnaire; PA, physical activity; WM, white matter; WMH, white matter hyperintensities.

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1. Introduction

It is hypothesized that physical activity (PA) helps to preserve and maintain cognitive function and decrease the risk of dementia and Alzheimer disease [1–4]. Change in cognitive ability has been associated with brain atrophy [5–17]. It has been shown that the brain atrophies with age due to volume loss in both white (WM) and gray matter (GM) and increase in white matter lesions [18]. GM has been shown to linearly decline with increasing age starting at early adulthood, while WM deterioration shows nonlinear changes [14,19,20]. WM has been shown to increase throughout adulthood, peaking at around the age of 40–60 years, followed by an accelerated decline starting around age 60 [14,19]. PA is also known to be negatively associated with age [21,22] and sedentary behavior (SB) is known to be positively associated with age [23]. This trend has been shown to start in the forties [22].

Cross-sectional studies have shown a positive relationship between GM and WM volumes in the older adult brain and physical fitness [24,25]. Furthermore, six months aerobic training was shown to increase both GM and WM volumes in older subjects [26]. A cross-sectional study, using questionnaire, showed PA levels to positively correlate with brain volumes [27]. Longitudinal studies, using questionnaires have shown that higher level of PA at baseline predicts larger GM volume [28–30], larger WM volume [29] and more total brain volume [29,30] in late life. Studies using objectively measured PA are needed to confirm these results.

Previous studies have shown that lower PA levels predict lower brain volumes and atrophy [28–30], indicating that PA affects brain volumes. Currently, there are no published studies on whether brain volumes or changes in brain volume, is associated with PA later in life. It might be expected that those with greater PA would have a history of greater brain volumes both in the past and in the present and show the best maintenance of brain volumes over time. The aims of this study are to quantify the prospective changes in magnetic resonance imaging (MRI)-derived brain atrophy measurements in a 5-year period and explore their association with objectively measured PA and SB in an older population. This study is the first to assess brain atrophy in a longitudinal study design in relation to objectively measured behavior outcomes. Furthermore, we will test the hypothesis that the association between brain volumes and the important behavioral variables, PA and SB, are independent of self-reported PA at baseline (SPA).

2. Methods

2.1. Study population and design

The Age, Gene/Environment Susceptibility Reykjavik Study (AGES-Reykjavik study) was a prospective cohort study designed to examine risk factors in relation to disease and disability in old age. The aim was to investigate the contributions of environmental factors, genetic susceptibility, and gene-environment interactions to aging of the neurocognitive, cardiovascular, musculoskeletal, body composition, and metabolic systems. The AGES-Reykjavik study is a continuation of the Reykjavik Study, which was initiated in 1967 by the Icelandic Heart Association and included men and women born in 1907–1935 and living in the Reykjavik area. From 2002 to 2006, new data were collected for the AGES-Reykjavik study, and details on the study design have been described elsewhere [31]. Data from this data collection was used as baseline measurements for the current study. The current study was a part of the AGESII-Reykjavik study which is a follow up of the AGES-Reykjavik study, with the time interval of approximately five years. Between April 2009 and June 2010, objective PA measurement by accelerometers was added to the AGESII-Reykjavik study test protocol [21]. During the PA sub-study measurement period, 1194 subjects participated in the AGESII-Reykjavik study and were eligible to be invited to participate in the sub-study. Of these, 150 participants were excluded for different reasons (e.g., blindness and other physical- and mental impairments), 84 refused and 294 did not participate because of scheduling conflicts. Five subjects lost the accelerometers. The remaining 671 (56.2%) participants received an accelerometer to measure their daily activity. Of these, 585 participants had four or more valid days (≥10 h of wear time) of useable accelerometry data. After excluding those with mild cognitive impairment (MCI), dementia or scored 24 or less on MMSE, 18 or less on the DSST test and did not have both brain measurements in AGES-Reykjavik study and AGESII-Reykjavik study, the final number of subjects was 352. The study was approved by the Icelandic National Bioethics Committee (VSN: 00-063), the Icelandic Data Protection Authority, and the institutional review board of the US National Institute on Aging, National Institutes of Health. Signed informed consent was given by all participants.

2.2. Assessment of PA

Participants were asked to wear the ActiGraph GT3X accelerometer (Actigraph Inc., Pensacola FL) monitor at the right hip for one complete week and to remove the monitor only before going to bed and during showers, bathing, or other water activities. Non-wear was defined as a period of at least 60 consecutive minutes during which the activity monitor recorded zero counts in all axes, allowing 1–2 min of vertical-axis counts between 0 and 100. A day of accelerometer wear was considered valid if the wear time was ≥10 h. Participants with fewer than four valid days over the week of measurement were excluded. Activity variables were derived from vertical-axis count values, and included: Total PA (TPA) defined as total counts during an average day (counts × day^{-1}) and SB as hours × day^{-1} of activity <100 count × min^{-1} during wear time. Lifestyle PA was defined as ≥760 counts × min^{-1} [21,32,33].

2.3. MRI image acquisition

MRI including T1-, proton density-, and T2-weighted and fluid-attenuated inversion recovery (FLAIR) images were acquired on a 1.5-Tesla Signa Twinspeed EXCITE system (General Electric Medical Systems, Waukesha, WI) in the AGES-Reykjavik study. Brain tissue volumes, including GM, WM, cerebral spinal fluid (CSF), and white matter hyperintensities (WMH), were generated separately, using the multispectral MR images and a high-throughput automatic image analysis pipeline, which is based on the Montreal Neurological Institute (MNI) pipeline and optimized for use in the AGES-Reykjavik study (AGES-RS/MNI pipeline) [18]. The key processing stages were as follows: stereotaxic registration was achieved after signal non-uniformity correction by an affine transformation of the T1-weighted images to the ICBM152 template. Intersequence registration was performed by registering images from the individual (T2/proton density, fluid-attenuated inversion recovery) sequences to the T1-weighted images in order to accurately align all image volumes acquired during an acquisition session. Linear signal intensity normalization was then applied to correct for signal intensity variations across images in the different sequences. Finally, tissue classification was achieved with an artificial neural network classifier. The absolute volumes of the four tissue types were subsequently calculated and converted to native space volumes using the scale factor obtained from the stereotaxic registration transformation. Intra-cranial volume (ICV) was calculated by adding the volumes of GM, normal WM, WMH and CSF. All tissue volumes are presented as percent of the total ICV. The acquisition and post-processing of the MRI have been described in detail

Table 1
Descriptive statistics for participants ($n = 352$) shown separately for women and men, for those above (GM high) and below the median for GM at baseline (GM low), and for those above (WM high) and below (low WM) the median for WM at baseline. Data are presented as mean (±SD).

Demographics	Men ($n = 137$)	Women ($n = 215$)	GM low ($n = 176$)[a]	GM high ($n = 176$)[a]	WM low ($n = 176$)[a]	WM high ($n = 176$)[a]
Age[a]	79.2 (4.0)	79.0 (4.6)	80.3 (4.6)	77.9 (3.7)	80.6 (4.5)	77.6 (3.7)
BMI ($kg \times m^{-2}$)[a]	26.9 (3.8)	26.9 (4.7)	26.2 (4.2)	27.6 (4.4)	27.1 (4.4)	26.8 (4.3)
Weight (kg)[a]	83.9 (13.6)	70.9 (13.4)	75.4 (15.1)	76.5 (14.7)	76.2 (15.9)	75.6 (13.9)
ICV (cm^3)[b]	1617 (122)	1409 (96)	1544 (145)	1435 (129)	1489 (144)	1490 (151)
GM (%)[b,c]	45.1 (2.7)	47.3 (2.7)	44.3 (1.9)	48.7 (1.7)	46.0 (2.8)	47.0 (2.9)
WM (%)[b,c]	26.1 (1.6)	26.2 (1.7)	26.0 (1.7)	26.4 (1.6)	24.9 (1.1)	27.5 (0.89)
GM-5yr (%)[a,c]	43.9 (2.7)	46.7 (2.8)	43.4 (2.1)	47.9 (1.9)	45.0 (3.0)	46.2 (3.0)
WM-5yr (%)[a,c]	24.7 (1.9)	24.9 (1.9)	24.5 (1.9)	25.1 (1.8)	23.4 (1.4)	26.2 (1.1)
Δ-GM (%)[d]	-1.2 (1.1)	-0.65 (1.0)	-0.91 (1.2)	-0.85 (0.93)	-0.92 (1.2)	-0.83 (1.0)
Δ-WM (%)[d]	-1.3 (0.83)	-1.4 (0.67)	-1.5 (0.82)	-1.2 (0.62)	-1.4 (0.81)	-1.3 (0.65)
Wear time ($h:min \times day^{-1}$)[a]	13:59 (1:18)	13:47 (1:13)	13:45 (1:20)	13:58 (1:10)	13:46 (1:20)	13:57 (1:10)
SB ($h:min \times day^{-1}$)[a]	10:31 (1:27)	10:06 (1:23)	10:20 (1:21)	10:11 (1:29)	10:30 (1:27)	10:01 (1:21)
TPA (1000 counts $\times day^{-1}$)[a]	120 (68)	114 (61)	106 (56)	127 (69)	101 (57)	132 (67)
Wear time PA (counts $\times min^{-1}$)[a]	143 (81)	136 (70)	127 (65)	151 (81)	121 (67)	157 (77)

BMI = Body max index; ICV = intra-cranial volume; GM = gray matter, WM = white matter, PA = physical activity; SB = sedentary behavior.
[a] Follow-up (5-yr) measurements.
[b] Baseline measurements.
[c] Brain volumes as percent of ICV.
[d] 5-year change (follow-up – baseline) (Δ).

elsewhere [18]. The methods used in the follow-up MRI were the same as used in the baseline measurements. The 5-year change (Δ) in GM and WM volumes was calculated as the difference between the relative volume at follow-up and baseline.

2.4. Covariates

Covariates measured at baseline included age, sex and education [34]. Weight and body mass index (BMI) [35] was measured at follow-up. BMI was calculated as weight [kg] divided by squared height [m^2]. Education was categorized as primary, secondary, college and university degree. SPA gathered from questionnaires from the AGES-Reykjavik study at baseline. Participants answered questions about how often they had participated in moderate or vigorous PA in the past 12 months (six categories to answer; (1) never, (2) rarely, (3) weekly but less than 1 h/week, (4) 1–3 h/week, (5) 4–7 h/week or (6) more than 7 h/week). The questions regarding PA were answered on a take-home questionnaire, that was reviewed by a trained interviewer when the participant came to a second visit to the clinic and returned the questionnaire. The following health factors measured at baseline were also used for adjustments: number of brain infarcts [18] depression [36], type 2 diabetes [37,38], mean arterial pressure (MAP) [39] and smoking status [30,38]. The presence of depression was assessed using the MINI International Neuropsychiatric Interview [40]. Participants were eligible for the MINI Interview if they had a score ≥6 on the 15-item Geriatric Depression Scale [41], had a history of anxiety or depression or were taking anti-depressant medication. Type 2 diabetes was defined as a fasting blood glucose level ≥7.0 mmol/L, the use of diabetic medication, or self-report of physician's diagnosis of diabetes. MAP was calculated from the participants diastolic- (DP) and systolic (SP) pressure (MAP = DP + [1/3] × [SP-DP]). Smoking status was assessed by questionnaire and assigned as current/former smoker versus never smoked. SB was adjusted for lifestyle PA and wear time in all statistical models.

Analyses were performed using IBM SPSS 20.0 (SPSS Inc., Chicago, IL). The association between the accelerometer variables and brain volume measurements was analyzed using linear regression models. The PA variables were log transformed to correct for skewness. For Tables 2 and 3, linear regressions were performed and several models were formed. First, Model 1 was adjusted for age and sex and coefficients reflect association for individual brain volume measurements variables in separate models. In Model 2 each brain volume variable was adjusted for age, sex, brain infarcts, days between baseline and follow-up measurements, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education. Further, in Model 3, all baseline measurement variables and 5-year change variables were entered in the same model adjusted for same covariates as in Model 2.

Table 2
Association between brain atrophy measures and total objectively measured physical activity. Brain volume measurements are presented as a percent of intra-cranial volume.

	Variables	Total physical activity ($counts \times day^{-1}$)			
		Std. β	Lower 95% CL	Upper 95% CL	*p*
Model 1#	GM[a]	0.16	0.047	0.27	0.0056
	WM[a]	0.20	0.093	0.31	0.00030
	GM-5yr[b]	0.24	0.12	0.35	<0.0001
	WM-5yr[b]	0.22	0.11	0.33	<0.0001
	Δ-GM[c]	0.17	0.063	0.27	0.0016
	Δ-WM[c]	0.090	-0.011	0.19	0.080
Model 2##	GM[a]	0.12	0.012	0.23	0.029
	WM[a]	0.13	0.031	0.23	0.010
	GM-5yr[b]	0.17	0.063	0.28	0.0021
	WM-5yr[b]	0.16	0.062	0.26	0.0016
	Δ-GM[c]	0.11	0.015	0.21	0.024
	Δ-WM[c]	0.11	0.0095	0.20	0.032
Model 3###	GM[a]	0.11	0.0028	0.22	0.044
	WM[a]	0.11	0.011	0.21	0.030
	Δ-GM[c]	0.14	0.047	0.24	0.0037
	Δ-WM[c]	0.11	0.010	0.21	0.030

GM = gray matter, WM = white matter.
# Model 1 = each variable entered separately and adjusted for age and sex.
Model 2 = Model 1 and additional adjustment for brain infarcts, days between baseline and follow-up measurements,education, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education.
Model 3 = baseline and the 5-year change brain measurement variables (Δ) included in the same model with same adjustments as in model 2.
[a] Baseline measurement.
[b] 5-yr follow-up measurement.
[c] 5-year change (follow-up – baseline) (Δ).

3. Results

3.1. Descriptive statistics

Descriptive characteristics for women and men are presented in Table 1. Participants were also subdivided into those with high (above median) and low (below median) baseline volumes of both

Table 3
Association between brain atrophy measures and objective sedentary behavior. Brain volume measurements are presented as a percent of intra-cranial volume.

	Variables	Sedentary behavior (hours × day^{-1})			
		Std. β	Lower 95% CL	Upper 95% CL	*p*
Model 1[#]	GM[a]	−0.011	−0.075	0.054	0.74
	WM[a]	−0.061	−0.12	0.00082	0.053
	GM-5yr[b]	−0.023	−0.091	0.044	0.49
	WM-5yr[b]	−0.092	−0.15	-0.031	0.0032
	Δ-GM[c]	−0.026	−0.085	0.033	0.38
	Δ-WM[c]	−0.080	−0.14	−0.024	0.0051
Model 2[##]	GM[a]	−0.0042	−0.074	0.065	0.91
	WM[a]	−0.043	−0.11	0.022	0.19
	GM-5yr[b]	−0.011	−0.083	0.061	0.76
	WM-5yr[b]	−0.084	−0.15	-0.019	0.012
	Δ-GM[c]	−0.015	−0.077	0.047	0.64
	Δ-WM[c]	−0.10	−0.17	−0.042	0.0010
Model 3[###]	GM[a]	0.015	−0.056	0.085	0.68
	WM[a]	−0.037	−0.10	0.028	0.26
	Δ-GM[c]	−0.034	−0.10	0.029	0.28
	Δ-WM[c]	−0.11	−0.17	−0.047	0.0007

GM – gray matter, WM – white matter.
[#] Model 1 = each variable entered separately and adjusted for age and sex, wear time and lifestyle PA.
[##] Model 2 = Model 1 and additional adjustment for brain infarcts, days between baseline and follow-up measurements,education, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education.
[###] Model 3 = baseline and the 5-year change brain measurement variables (Δ) included in the same model with same adjustments as in model 2.
[a] Baseline measurement.
[b] 5-yr follow-up measurement.
[c] 5-year change (follow-up – baseline) (Δ).

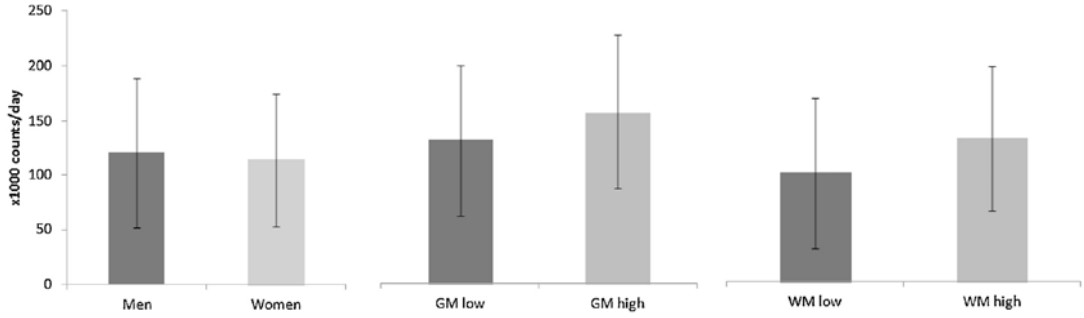

Fig. 1. The mean (±SD) amount of total physical activity (TPA) for men and women, those with low gray matter (GM) and high GM, and those with low white matter (WM) and high WM.

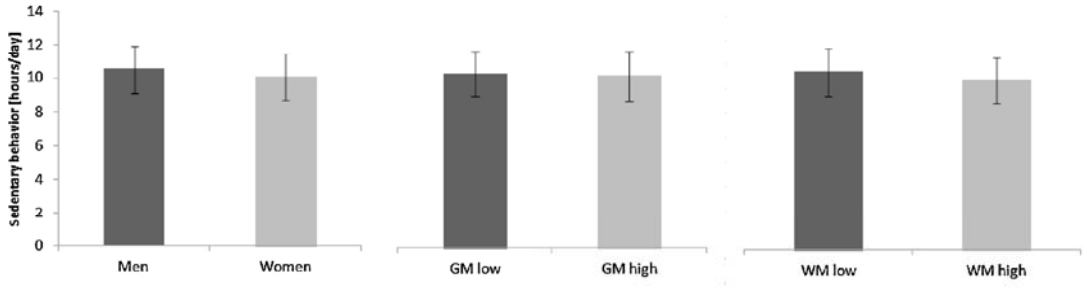

Fig. 2. The mean (±SD) amount of sedentary behavior (SB) for men and women, those with low gray matter (GM) and high GM, and those with low white matter (WM) and high WM.

GM and WM. TPA and SB for men and women, for low and high GM, and for low and high WM, are presented in Fig. 1 and Fig. 2, respectively. The mean age of the participants receiving an accelerometer at the AGESII-Reykjavik study was 79.1 (SD 4.4) years. Participants with lower GM averaged 106,000 counts × day^{-1} in TPA, but those with higher GM averaged 127,000 counts × day^{-1} in TPA. Participants with lower WM averaged 101,000 counts × day^{-1} in TPA, but those with higher WM averaged 132,000 in counts × day^{-1} in TPA. For SB, those with lower GM spent 10:20 h:min × day^{-1} sedentary, but those with higher GM spent 10:11 h:min × day^{-1} sedentary.

Participants with lower WM spent 10:30 h:min × day^{-1}, but those with higher WM spent 10:01 h:min × day^{-1} in SB.

3.1.1. Regression analysis of physical activity and brain volume

Results from linear regression models for TPA are shown in Table 2. With adjustments for age and sex (Models 1), all brain measurement variables were separately and significantly positively associated with TPA (all $p < 0.05$), except the 5-year change in WM. Adding brain infarcts, days between baseline and follow-up measurements, SPA, BMI, depression, MAP, type 2 diabetes, smoking status and education as covariates (Model 2), did not change the significance or direction of the correlations, with the exception of the 5-year change in WM, which was found to have a significant, positive correlation with TPA ($p < 0.05$). When both baseline brain volume and the 5-year brain volume change were included in the same model (Model 3), which also adjusted for the above potential confounding variables, all brain volumes were significantly associated with TPA (all $p < 0.05$). Less brain volume at baseline and more 5-year loss, predict less PA.

3.1.2. Regression analysis of sedentary behavior and brain volume

Results from linear regression models for SB are shown in Table 3. For SB, only WM at follow-up ($\beta = -0.092$; $p = 0.0032$) and the 5-year change in WM ($\beta = -0.080$; $p = 0.0051$) were separately associated, negatively, with SB. Less WM at baseline and more 5-year decrease, predict more SB. When adjusting the models for the above covariates, lifestyle PA and wear time, the same brain parameters were significantly negatively associated with SB (WM at follow-up: $\beta = -0.084$; $p = 0.012$); (5-year change in WM: $\beta = -0.10$; $p = 0.0010$). These associations remained in Model 3.

4. Discussion

The main finding of this study is that more GM and WM at both baseline and follow-up are independently associated with more TPA, even when adjusted for self-reported PA questionnaire (SPA) and several other potential confounding variables. Furthermore, a 5-year change in both GM and WM was associated with less TPA. In addition, less WM at follow-up and the 5-year change in WM was independently associated with more SB, also after adjusting for lifestyle PA, wear time, SPA and other potential confounding variables. The results suggest that maintenance of brain volume is associated with PA in older adults and that WM atrophy is associated with SB, independent of lifestyle PA and SPA. Thus: (a) more GM and WM volumes, and less 5-year atrophy in these volumes, predicts more PA; and (b) more 5-year atrophy in WM, predicts more SB.

Previous longitudinal studies have shown higher PA and structured exercise to be associated with more global or regional brain volumes later in life, both GM and WM [28–30,42]. Most of those studies use self-reported questionnaires which are known to misestimate PA levels and SB in comparison to more objective measurements [43,44]. Interestingly, two longitudinal studies found no association between PA and brain volumes after adjusting for confounding factors [29,30]. However, in both studies the participants were slightly younger than in the present study. In the present study, we adjust for PA measured at baseline with questionnaire (SPA) when examining change in the brain measurements. Therefore, the observed association between brain volumes and brain volume changes on the one hand, and PA and SB at follow-up on the other hand, are independent of the SPA classification at baseline. Our results thus may suggest that the longitudinal relationship between brain volumes and PA could also be the other way around, i.e. brain atrophy associates with subsequent decline in PA and more SB. This bidirectional relationship, i.e. brain atrophy causes less PA and vice versa, forms a pattern that needs intervention. By breaking that bidirectional relationship, better physical- and brain health could be gained.

Only the 5-year decrease in WM independently predicted more SB after adjusting for lifestyle PA, wear time and potential confounding variables. In older people, SB is known to have the highest prevalence of all activity types compared to any other age group [23,45,46]. We have previously shown in this cohort that participants were on average sedentary for 10.1 h × day, or 74.5% of their non-sleeping time [21]. The increase in time spent in SB after the age of 60 may be due to positive factors such as increased leisure time following retirement or to negative factors such as worsening health conditions [23]. SB has been identified as a distinct risk factor for poor health [47] and mortality [48]. With increasing age, nerve fiber activity declines and affects brain function [49,50]. A recent study suggests that among older adults, the structural integrity of WM is not only dependent on levels of PA, but also on the amount of remaining time spent sedentary [51].

Future studies should also investigate whether atrophy of particular regions in the brain are more potent than other regions in terms of diminishing PA and increasing SB. Many studies have demonstrated the effects of both planned exercise and PA in changing the volume of most regions of the brain [26–28,30,35,42,52–55]. Blood flow in the brain has been shown to vary between types of exercise and intensities [56,57]. Furthermore, it has been well documented that increased blood flow in the brain during exercises promotes the development of new neurons [58–60] and thereby delays brain structural and functional decline [61]. Although, PA seems to affect some regions of the brain more than others, it cannot be assumed that the atrophy of the same regions are most potent in affecting the PA and SB.

The present study is based on the well-characterized, population based AGES-Reykjavik cohort of older men and women [31]. This cohort consists of healthy older adults of Caucasian descent. It is thus expected that these findings can be generalized for most western populations in this age range. The main strengths of this study include objectively measured PA at study follow-up. Also, we have a longitudinal design of brain measurements with five years interval. Earlier it has been shown that participants who wore the accelerometers had similar characteristics compared with those participants who did not receive an accelerometer [21]. Nonetheless, we acknowledge several limitations in the present study. PA at baseline was not measured by an objective method, as self-report questionnaires were used. Therefore, we did not have similar measurements of the PA and SB at baseline and at follow-up, and SB was not measured at baseline. It is possible that if objective measurement of PA at baseline would have been available and used to adjust the statistical models, the observed association would have become attenuated. A longitudinal study using objective measurements both at baseline and follow-up would be beneficial to further test our hypothesis. Also, even though objective measurements are considered to be more accurate than subjective measurements, it is known that hip-worn accelerometers fail to detect some movements, like upper body movements during activities such as weight lifting and heavy carrying. They also have limitations on detecting non-ambulatory activities like cycling [62], activity that is not common in this age group in Iceland [63]. However, a quarter of the participants in this cohort of older Icelanders, reported swimming as an exercise [21], which is not included in the presented TPA. Since we only have objective measurements at follow-up, it is unclear if the relationships observed are uni- or bi-directional. Other studies are necessary to identify the direction of these relationships.

5. Conclusions

Our study confirms that there is an association between brain atrophy and PA. We also show an association between brain atrophy and SB, independent of lifestyle PA. These relationships are robust to adjustment by a number of confounders. This study provides additional evidence of the positive association of PA and the brain. PA interventions aimed at alleviating this association could have important public health impact.

Disclosure statement

The authors have no conflicts to disclose.

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