Impact of using aging-in-place technologies on quality of life: Results from a randomized controlled trial in four European countries

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Abstract

Background: It is widely recognized that technologies have the potential to contribute to high-quality long-term care for older people at home. Evidence from past RCTs partly confirms the positive effects of technology use, although results are mixed and various questions remain unanswered.
Objective: This study aimed to demonstrate the beneficial mid- and long-term effects of using aging-in-place technologies on quality of life (QoL) indicators like perceived safety, control, and participation (ATQoL scale) and other specific psychosocial outcomes (PIADS) as well as general health-related QoL (EQ-5D-5L Index value and Health today).
Method: We conducted an RCT with 281 older people in Austria, Italy, the Netherlands, and Slovenia. Persons in the intervention group (n=143) obtained a bundle of smart home and assistive technologies which they used for 6 or 13 months in their private homes. Persons in the control group (n=138) received no intervention. Three hypotheses were tested with Generalized Linear Mixed Models.
Results: We found slightly positive impacts of technology use on some of the specific QoL indicators for persons who used the technologies for 13 months and were relatively motivated and healthy. No, or even detrimental, effects emerged after 6 months. However, persons who used the emergency watch frequently perceived more favorable outcomes than those who used it rarely. Effects had small to medium standardized effect sizes. No effects emerged for the general health-related QoL measure.
Conclusion: Despite study limitations (and the COVID-19 pandemic) we conclude that aging-in-place technologies can mitigate adverse age-related developments, and have stabilizing effects on the QoL of older persons. Our trial showed that outcome indicators that are closely related to technology use should be preferred to general indicators. Findings now have to be consolidated in meta-analyses to paint a clearer picture of the beneficial effects of technology use.

Keywords: aging-in-place technologies, assistive technologies, AAL, quality of life, older adults

Introduction

Recently, the importance of aging-in-place, i.e. enabling older people to live autonomously in their homes and communities for as long as possible, and its policy implications, have been highlighted (Ahn, Kwon, & Kang, 2017; Marshall et al., 2022). However, in many EU countries, this concept is not sufficiently supported by social policies (Spasova, Baeten, & Vanhercke, 2018) and the care needs of older people are unmet, even in former exemplary countries (Kröger, Puthenparambil, & van Aerschot, 2019). Therefore, researchers have emphasized the need for technological solutions which facilitate aging-in-place (Rogers & Mitzner, 2017) and help address the challenges for aging populations in the context of frailty and chronic disease (Keränen et al., 2017; Uei, Kuo, Tsai, & Kuo, 2017). Recent European Commission reports highlight the benefits of using electronic assistive technologies in long-term care, recognize their potential to improve the quality of life (QoL) of older people and call for better use of both off-the-shelf technologies and technologies specifically designed for older people, in spite of some limitations and challenges (Social Protection Committee and the European Commission, 2021; Zigante, 2020).

QoL impacts of technology use

QoL is a complex concept for which many definitions and measurement approaches have been proposed (Dijkers, 2003; The WHOQOL Group, 1998). Common to many frameworks and models about what QoL means is that they are multidimensional, with some overlap and influences between the dimensions, and they rely primarily on subjective assessment (Bowling & Gabriel, 2004; Veenhoven, 2000). As Veenhoven (2000) states, it is practically impossible to assess QoL comprehensively, and researchers in the field of gerontechnology in fact often concentrate on significant areas like health-related QoL (Gellis et al., 2012) or social inclusion (Czaja, Boot, Charness, Rogers, & Sharit, 2018). There are several scales that measure QoL in older people, e.g., the WHOQOL-OLD (Power, Quinn, & Schmidt, 2005) or the CASP-19 (Hyde, Wiggins, Higgs, & Blane, 2003). A few of them directly assess the impact of using (electronic) assistive technologies like the Psychosocial Impact of Assistive Devices Scale (PIADS) (Jutai & Day, 2002) and the Assistive Technologies Quality of Life (ATQoL) scale (Agree & Freedman, 2011) which were both used in the present study. In the following, we present an overview of the current empirical evidence on the effects of technology use on the QoL areas which are relevant to this study.

Health-related QoL

A systematic review of the effects of smart home and monitoring technologies on older people with chronic illnesses found beneficial effects on some health-related factors but not on health-related QoL (Liu, Stroulia, Nikolaidis, Miguel-Cruz, & Rios Rincon, 2016). The authors attribute this, amongst others, to the diversity of addressed health-related and functional impairments. Another recent review article about the effects of electronic assistive devices for community-dwelling older people found no or little evidence of the effectivity of the technologies in 8 of the studies, however, 8 demonstrated that physical and mental well-being can be improved by technology use (Song & van der Cammen, 2019).

Often, studies included in reviews are methodologically very different and of mixed quality. Few studies are field studies, and even fewer are randomized controlled trials (RCTs). Here, we will primarily refer to studies with an RCT design, which allow inferring causal relationships between technology use and outcome variables. One of them tested a bundle of assistive and monitoring technologies for older people at home with a large sample over a one-year period (Hirani et al., 2014). At the end of the trial, the intervention group (IG) had a significantly higher mental health status than the control group (CG). However, health-related QoL, as well as depressive symptoms, deteriorated for all participants over time; tendentially, persons in the IG were less depressed than those in the CG. No interaction effects (Time x Group) got significant. In another RCT, an emergency button with a speaker for communication, including emergency services was tested for three months (Morgenstern, Adelman, Hughes, Wing, & Lisabeth, 2015). No significant differences between IG and CG over time were found for health-related QoL, anxiety, and depression. Also in the PRISM trial, which tested a software for everyday organization, contact with others, and information search (Czaja et al., 2018), over the duration of the 12-month test phase, some deterioration in physical functioning occurred in all participants, but the participants in the IG perceived to have more energy than the CG. Other RCTs found that individuals with higher primary healthcare needs experienced a positive impact of technology use on their mental QoL (Gustafson et al., 2021), technology use over time might lead to a less pronounced increase in perception of pain (Mann, Ottenbacher, Fraas, Tomita, & Granger, 1999) and overall cognitive and physical status deteriorate less if aging-in-place technologies are used (Tomita, Mann, Stanton, Tomita, & Sundar, 2007). Overall, it has to be emphasized that also RCTs have methodological limitations (discussed comprehensively by Bieg, Gerdenitsch, Schwaninger, Kern, & Frauenberger, 2022) which might lead to non-significant effects. However, there seems to be a tendency in the studies about technologies being able to slow down a general decline of perceived health and health-related QoL over time.

Perceived safety

Researchers have observed a discrepancy in technology outcomes according to study design (Damant, Knapp, Freddolino, & Lombard, 2017), which also seems to be the case for perceived safety: in contrast to quantitative (long-term) studies, those with qualitative or methodologically less rigorous design seem to discover more positive results (Åkerlind, Martin, & Gustafsson, 2018; Jaschinski & Ben Allouch, 2019; Lukas, Maucher, Bugler, Flemming, & Meyer, 2021; Rohne, Boysen, & Ausen, 2017; Sixsmith, 2000; van Hoof, Kort, Rutten, & Duijnstee, 2011; Watson, Bearpark, & Ling, 2021). To our knowledge, only one RCT studied the effects of active assisted living (AAL) technology use on perceptions of safety – it failed to demonstrate significant effects (Bieg et al., 2022). Apart from methodological issues which can explain weak or null effects, researchers have pointed out that the personalization, application outside the home, and technological up-to-dateness of technologies are indispensable for safety perception (Boström, Kjellström, Malmberg, & Björklund, 2011). Furthermore, participants may have expectations about the technology in terms of its impact on feeling safe, which then cannot be fulfilled due to a lack of functionalities or functioning (Mahoney, Mahoney, & Liss, 2009).

Autonomy and control in everyday life

Older people have strongly associated aging-in-place with independence and autonomy (Wiles, Leibing, Guberman, Reeve, & Allen, 2012). Furthermore, as a QoL indicator, and as an outcome of technology use, it has been described as very important (Bowling et al., 2003; Peek et al., 2016; Peek, Aarts, & Wouters, 2017; Rogers & Mitzner, 2017). The mixed evidence for the effects of smart home and activity monitoring technologies on perceived independence or the degree of activity and functional ability, which allows control in everyday life, is often based on small-scale or descriptive studies (Brandt, Samuelsson, Töytäri, & Salminen, 2011; Dupuy, Consel, & Sauzéon, 2016; Lexis et al., 2013). Also several RCTs have included variables like autonomy or control as outcome variables – however, their results are not able to demonstrate clear beneficial effects of technology use. One trial tested a multitask AAL platform (Dupuy, Froger, Consel, & Sauzéon, 2017; Dupuy & Sauzéon, 2020) in which the IG participants did not perceive an improvement of instrumental activities of daily living (IADLs, Lawton & Brody, 1969) after 6 months, however, some tendencies for beneficial outcomes after 9 months could be found. Furthermore, caregivers estimated that functional ability had decreased slightly for the CG and remained stable for the IG over 9 months. Another RCT investigating if aging-in-place technologies had an effect on the perceived autonomy and competence as parts of self-determination (Ryan & Deci, 2000) could not find significant effects either (Bieg et al., 2022). Also using a system of assistive technical and non-technical solutions for motor and sensory impairments did not prevent from functional status deteriorating (Mann et al., 1999). In contrast, others concluded that using aging-in-place technologies could positively influence independent living at home (Tomita et al., 2007) and lead to a stable perception of autonomy in the IG over time while decreasing in the CG (Schmidt et al., 2019). Interestingly, up to now, the Psychosocial Impacts of Assistive Devices Scale PIADS, which measures various outcomes of assistive technologies on aspects like independence, control, and competence in everyday life, has only been used rarely in empirical studies outside the evaluation of technologies for persons with physical or mental disabilities, i.e. for older people living at home (Hvalič-Touzery, Šetinc, & Dolničar, 2022; Isabet, Rigaud, Li, & Pino, 2022; Orellano-Colón et al., 2020). The present study uses the scale for the first time in an RCT to measure the outcomes of using an AAL bundle.

Participation in social and other pleasant activities

Another important aspect of QoL for older people is participation in social or other enjoyable activities (Bowling et al., 2003; Power et al., 2005). Some studies measured technology effects on the functional and motor prerequisites of participation (Zander, Johansson-Pajala, & Gustafsson, 2020). Others investigated the effects of everyday ICT, self-help, and support websites for persons with chronic conditions or cognitive impairments on social participation – many beneficial outcomes were found, even though negative and null effects emerged as well (Damant et al., 2017; Morris et al., 2014). However, for the use of telecare and monitoring technologies, there seems less evidence of positive social participation outcomes (Damant et al., 2017).

Results from intervention studies which can be compared to our trial show mixed effects. Czaja et al. (2018) found that all study participants experienced less loneliness and social isolation after trial participation. Furthermore, after 6 months, IG participants perceived a greater decrease in loneliness, a greater increase in social support, and tendentially a greater decline in social isolation compared to the CG; after 12 months, the effects disappeared. In a study about similar technologies, no significant effects emerged regarding social support (Gustafson et al., 2015; Gustafson et al., 2021), also Morgenstern et al. (2015) found no differences in IG and CG regarding social inclusion after the technology intervention. In contrast, Mann et al. (1999) showed that the social integration of all participants deteriorated after the 18 months trial duration. Yet a different result was reported by Schmidt et al. (2019) – a decline in participation of the CG compared to more stable participation of the IG was observed after the intervention.

Our study adds several important insights to the existing body of research. First, the literature review above shows that the questions about the beneficial effects of technology use on older adults are far from being answered. Only a few RCTs tested a bundle of aging-in-place technologies for a longer period in the homes of older people (Bieg et al., 2022; Dupuy & Sauzéon, 2020; Hirani et al., 2014; Tomita et al., 2007) which is not sufficient to speak of robust evidence. Furthermore, there still is no clarity about which technologies for how long have which effects on the QoL and well-being of older people, also due to the considerable variability in studies concerning the type of technologies used and the outcomes measured (Khosravi, Rezvani, & Wiewiora, 2016; Kristoffersson, Kolkowska, & Loutfi, 2019; Siegel & Dorner, 2017). In our RCT, we addressed both issues: First, we distinguished between different features of the technology bundle when analyzing effects (the tablet as well as the emergency watch); second, we used a highly specific measurement tool for technology outcomes (PIADS), which might lead to meaningful results (Bieg et al., 2022). Furthermore, none of the previous RCTs investigated if the different intensities of technology use affected outcome variables, whereas, in our data analysis, we compared the older persons who used the technologies (rather) frequently with those who used them rarely or never.

Objectives of the present study

The present RCT was conducted during the European AAL project "i-evAALution – integrating and evaluating AAL solutions", and ran from 2019 to 2021 in Austria, Italy, Slovenia, and the Netherlands. Its main aim was to demonstrate causal effects on QoL-indicators of the use of a bundle of aging-in-place technologies, consisting of an emergency watch, a wireless emergency button, a tablet, and smart home devices. It was assumed that QoL-benefits after mid- and long-term technology use should emerge when comparing older participants in the IG, who had the technologies installed in their homes for 6 or 13 months, with the participants in the CG, who received no intervention.

Our research hypotheses were as follows:

H1a: After 6 months, the QoL of the IG participants increases (or decreases less) compared to that of the CG participants.

H1b: After 13 months, the QoL of the IG participants increases (or decreases less) compared to that of the CG participants.

H2a: After 6 months, IG participants perceive more positive psychosocial effects of the technology use compared to their expectations at baseline.

H2b: After 13 months, IG participants perceive more positive psychosocial effects of the technology use compared to their expectations at baseline.

H3a: After 6 months, the QoL of IG participants who use the technologies more frequently increases (or decreases less) compared to that of participants who use the technologies less frequently.

H3b: After 13 months, the QoL of IG participants who use the technologies more frequently increases (or decreases less) compared to that of participants who use the technologies less frequently.

Measures

Primary outcome measures

Schulz et al. (2013) define QoL technologies as "designed to impact the QoL of individuals who use them. […] their impact could be evaluated using QoL instruments to assess both generic effects as well as the specific domains targeted by a particular technology" (page IX). Following this reasoning, we included the EQ-5D-5L (Herdman et al., 2011) as a general measure of perceived health-related QoL, as well as the two specific measures ATQoL (Agree & Freedman, 2011) and PIADS (Day & Jutai, 1996; Jutai & Day, 2002). The EQ-5D-5L includes five items on mobility, self-care, usual activities, pain/discomfort, and anxiety/depression, whose ratings can be converted into country-related index values (we chose the Dutch value set for the conversion), plus a visual analogue scale from 0 to 100 about the current perceived health. The ATQoL consists of three items that capture the feelings of safety and control when performing daily activities, as well as perceived participation in enjoyable activities, measured on a 5-point Likert scale. We adapted the original questions ("Because you use these [technologies], how much safer do you feel when you do your daily activities?") so they assessed participants' general feelings during the past 4 weeks – in this way we could administer the items to IG as well as CG participants. PIADS, the second measure specific to the (expected) outcomes of technology use comprises the three subscales Competence, Adaptability, and Self-esteem which are measured on a 7-point Likert scale. In Slovenia, PIADS was administered only in its 10-item short form (Jutai et al., 2007) due to the long version's complexity and the considerable length of the overall questionnaires. Therefore, we were able to analyze results for the three subscales with data from participants from three countries, whereas the short version could be analyzed for all test persons. EQ-5D-5L and ATQoL were completed by all persons at B1, M6, and M13, whereas PIADS was only filled in by the IG participants at B2, M6, and M13 (*Figure 1*).

Additional measures

We used several technology acceptance measures to evaluate the bundle, mainly based on the Technology Acceptance Model (Davis, 1989). However, in this article, we only include technology acceptance as the extent to which participants a) used the emergency watch, and b) used the tablet frequently vs. rarely (see H3). Frequency of use was assessed by self-developed questions which asked if participants had used the devices never, rarely, sometimes, often, or very often since the last measurement point. In addition, we collected log data through the middleware and were thus able to conclude more objectively how much the devices were potentially used on average over the whole trial. It was not possible to collect usage data about the smart home components. Due to the onset of the COVID-19 pandemic and its expected substantial impact on our primary outcome measures, the following control variables (all self-developed items, except b) were assessed at M6 and M13: (a) Change of living situation, i.e. if the older persons had temporarily moved somewhere else; (b) Perceived current QoL compared to before the pandemic (based on an item from the SF-36, Ware & Sherbourne, 1992); (c) Perceived current frequency of use of everyday IT for communication, information, entertainment, and safety, compared to before the pandemic; (d)

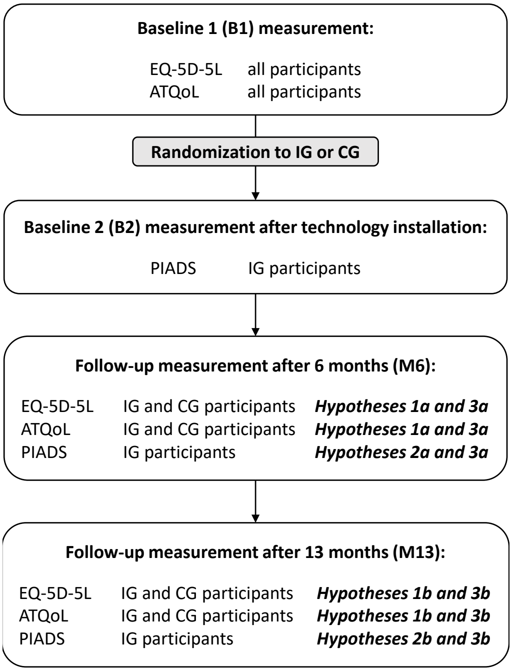

Figure 1. Procedure diagram, including measurement scales, participant groups and hypotheses

Perceived influence of the COVID-19 pandemic on the use of the i-evAALution technologies.

Methods

Study design

We conducted a two-group parallel nonblinded RCT with half of the participants being allocated to the IG, and half to the CG. Randomization was carried out after the completion of the baseline 1 (B1) questionnaire. IG participants filled in an additional baseline questionnaire (B2), containing several technology-related measures, after the technology installation and a training session. It was planned to administer the follow-up questionnaires 4 and 12 months after B1, however, due to a delay in the technology integration as well as contact restrictions during the COVID-19 pandemic, they were filled in after 6 and 13 months (M6 and M13) on average. As a recognition of the participants' time and effort, every pilot site planned local events during and/or non-monetary compensations at the end of the trial. The procedural diagram in *Figure 1* gives an overview of the different measurement points, measurement tools, participants, and respective hypotheses.

The trial was conducted in Austria (3 sites), Italy (1 site), the Netherlands (2 sites), and Slovenia (1 site). The project ended in March 2021, thus, recruitment stopped in September 2020, to guarantee the participation of at least 6 months. To enhance the objectivity and internal validity of our interventions and data collection, we standardized procedures as much as possible, with guidelines for the technology training and installation as well as other contacts with participants. The trial was approved by the Board for Ethical Questions in Science of the University of Innsbruck, Austria (Certificate of good standing 28/2019, 17 June 2019) and the Ethics committee of the health administration in South Tyrol, Italy (report no. 66-2019, 19 September 2019).

Participants

The eligibility criteria for participants were being 65 years of age or older, living in a private or assisted living apartment, having no severe cognitive impairment, being committed to testing the whole technology bundle for 12 months, having a private reference person like a family member or neighbor willing to participate as well, accepting the random allocation to IG or CG, and having sufficient language skills. In two trial sites, cognitive abilities were assessed with the Mini Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975), and the other sites relied on the assessments of professional care personnel or project staff.

The consortium faced various recruitment difficulties, especially due to the onset of the COVID-19 pandemic. Therefore, in the Austrian pilot sites, 9 persons aged 51 to 64 years with chronic conditions were admitted to the trial, as were participants without reference persons – in total 13% of the older persons participated on their own. Recruitment took place via senior organizations, local online and print articles, radio ads, and information flyers. Interested persons were invited to information events and/or face-to-face meetings where attention was paid to clearly explain the randomization process to prevent disappointment due to CG assignment and in consequence dropout (Skingley, Bungay, Clift, & Warden, 2014) as well as privacy issues, a concern of many older people using technologies (Peek et al., 2014).

Intervention

The i-evAALution bundle was assembled to cover five main categories of the TAALXONOMY, a taxonomy for the classification of AAL products and services (www.taalxonomy.eu/en/): Health and care, safety and security, living and buildings, information and communication, and leisure and culture. These categories were developed in an elaborate process, based on the one hand on relevant classification system like the ISO9999 for assistive products (www.iso.org/standard/50982.html) or the German standardization roadmap AAL (VDE, 2014). On the other hand, several QoL models were woven into the taxonomy, with the dimensions of the WHOQOL-100 (The WHOQOL Group, 1998) and

Figure 2. The i-evAALution technology bundle (including 2PCS antenna and smart home gateway)

the WHOQOL-OLD (Power et al., 2005) in the center, being matched and enriched with others, like the WHOQOL-AGE (Caballero et al., 2013), the Adult Social Care Outcome Toolkit – ASCOT (Netten et al., 2012), the OECD Better Life Index – BLI (www.oecdbetterlifeindex.org), and the International Classification of Functioning, Disability, and Health – ICF (Ustün, Chatterji, Bickenbach, Kostanjsek, & Schneider, 2003).

The specific technological components were chosen to cover the need of many older people to live at home autonomously for as long as possible (Ahn & Carucci Goss, 2006; Fausset, Kelly, Rogers, & Fisk, 2011). The technologies were supposed to have a positive effect on the perceived safety and well-being of older people at home and outside (primary effect according to Schulz et al., 2013) and thereby increase mobility and hence the possibility to participate in pleasant and social activities (secondary effect according to Schulz et al., 2013). From a technical point of view, the bundle should combine components freely available on the market (smart home technologies) with reliably functioning devices developed specifically for older people, thereby creating new beneficial functionalities. Furthermore, it was assumed that relatives or other close persons are often unable to provide the desired level of support due to their own family and work commitments (Czaja, 2016) which should be addressed by the technologies as well.

The bundle contained the following devices (*Figure 2*):

- An emergency watch with an alarm button, automatic fall detection, and localization functionality (by 2PCS SOLUTIONS Ltd.)
- A stationary alarm button (by 2PCS SOLUTIONS Ltd.)
- Smart home devices, i.e., movement and door sensors, smart plugs, a smoke detector, and smart light switches (by Livisi Ltd.)
- A tablet, "HomeTab", with an alarm button, a calendar with a reminder functionality for appointments, 4 games, a button to control lights connected with the smart home system, and a website with local information for older people (by Eurotronik Kranj / Caretronic d.o.o.).

The first three components of the bundle are available on the market while the tablet was adapted based on an existing care tablet. The integration and interoperability of the single devices by a middleware platform were achieved during the project. All participants were provided with an internet connection via SIM card and router. The table in the appendix gives an overview of the covered functionalities.

Manual alarms triggered through the emergency watch, the tablet, the stationary alarm button, or the automatic fall detection caused a speak-listen connection through the watch with professional emergency call centers or reference persons. Hierarchical processes ensured the emergency was not closed until the participant was cared for. If older persons participated without a reference person, either the professional emergency call center or project staff took over the respective tasks. Localizing a missing person via the emergency watch was not possible without a participating reference person.

IG participants were free to use any of the devices and functionalities. If they had been using a conventional emergency device before the trial, they were urged to continue doing so. Everyone received a 1–2-hour technology training session as well as a printed user manual. Due to the outbreak of the COVID-19 pandemic, additional sessions could not be offered. Technical assistance during the trial was provided by pilot partners and the involved technology suppliers.

Sample size

When designing the RCT for the project proposal, the a priori sample size for an independent sample t-test, assuming a small effect size (Cohen's $d = 0.20$) was calculated using the freeware tool G*Power (Faul & Erdfelder, 2007). With the power set to $1 - \beta = 0.80$, and the significance threshold to $\alpha = 0.05$, a required total sample size of $n = 788$ was obtained. However, for the actual analysis method, Generalized Linear Mixed Models (GLMMs), the original calculation must be revisited. It has been stated that conventional sample size calculations are not suitable for multilevel models, and that appropriate calculations are very complex with no easy way around this complexity (Kreft & Leeuw, 1998). The only valid rule of thumb is that sample sizes on the highest level (in our case on the level of individuals) should be as large as possible (Kreft

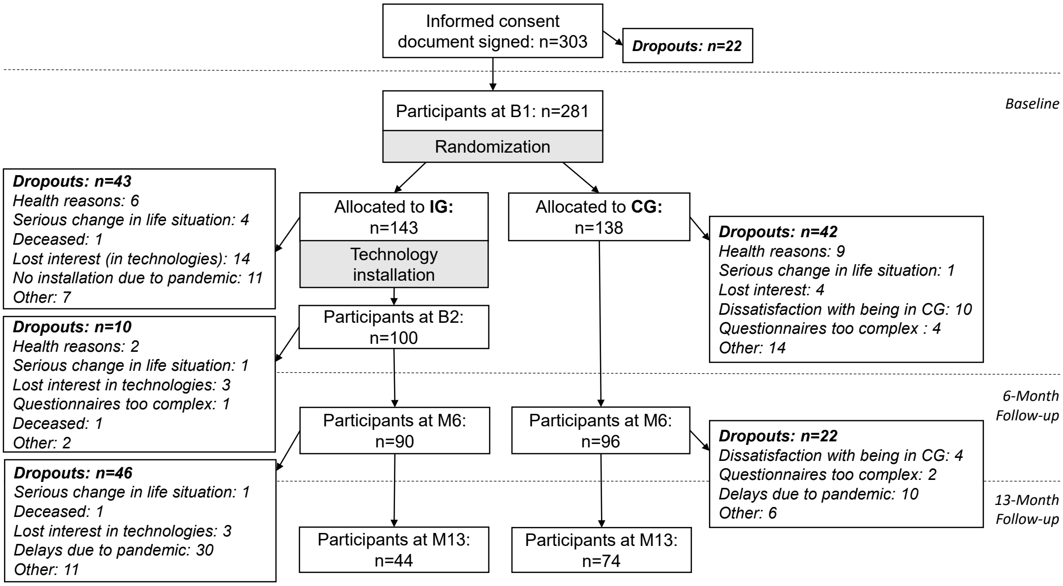

Figure 3. CONSORT flow diagram

& Leeuw, 1998; Snijders, 2005). Therefore, we decided that a posteriori power calculations were not proportionate as, with a sample size of 281 persons and considerable attrition (*Figure 3*), our analyses for the detection of QoL effects were most likely underpowered anyway.

Randomization

The randomization had a stratified, permuted, random block design with an allocation ratio of 1:1. We stratified for the pilot site and living situation (living alone vs. not alone) so that in each site an equal size of IG and CG was obtained, with single and multi-person households distributed evenly. If two older persons of the same household participated both were assigned to either IG or CG. To minimize the risk of manipulation, a member of the project staff who was not involved in the recruitment created blocks with randomly varied sizes and a random allocation sequence, and then transferred both to the backend of a Microsoft Access database, which was used for the allocation. Furthermore, for every participant, an ID consisting of the initials of first name and surname, as well as the birth year had to be entered into the database in addition to the fully pseudonymized project IDs to prevent manipulation by exchanging IDs.

Statistical methods

To test our hypotheses, we used 2-level GLMMs as they can handle non-independent and missing data (Brauer & Curtin, 2018) as well as unmet assumptions like non-normality of residuals and sphericity problems (Ng & Cribbie, 2017), all being issues in our data set. For every analysis, assumptions were checked graphically and numerically, as well as by calculating ANOVAs with repeated measures (Hox & van de Schoot, 2013). For the distributions of the outcome variable errors that were positively skewed, we assumed gamma distributions and log links in the GLMMs. If distributions showed overdispersion (variance > mean) we additionally checked if models with negative binomial distributions and log links would result in a better fit (Bono, Alarcón, & Blanca, 2021). If distributions only had small deviations from normality, we additionally fit linear models with identity links. We conducted all outcome analyses including two measurement points (B1 or B2 and M6) and three measurement points (B1 or B2, M6, and M13), as the attrition was substantial between M6 and M13, with persons who participated until M13 probably being healthier, and more motivated than persons who only remained until M6.

For every analysis, three models were built. In the first model, we included a group variable, a time variable, and their interaction. In the second model, we added the covariates age, gender, education, perceived economic situation, and QoL-deterioration due to the COVID-19 pandemic, and in the third model the covariates about change in use of everyday IT for communication, information, entertainment, and safety during the pandemic. It was not possible to include nationality, as participant numbers in the project countries were partly too small. Significant second or third models were always compared with the previous one by comparing the goodness-of-fit index Akaike corrected measures (AICC). Below, for every analysis, we present the effects of the model with the lowest AICC.

Table 1. Baseline sociodemographic characteristics and QoL measures

Variable	IG (N = 143)	CG (N = 138)	Difference (F-, U- or χ²-value)**
Sociodemographics			
Age	76.5 (8.1)*, range: 51-93	77.9 (7.6), range: 60-97	2.10
Female	95 (66.4)	99 (71.7)	0.93
Country			0.44
AT	65 (45.5)	58 (42.0)	
IT	36 (25.2)	36 (26.1)	
NL	14 (9.8)	16 (11.6)	
SI	28 (19.6)	28 (20.3)	
Education			0.47
Low	34 (24.8)	39 (28.5)	
Medium	80 (58.4)	76 (55.5)	
Advanced	23 (16.8)	22 (16.1)	
Lives alone	102 (71.3)	98 (71.0)	0.003
Primary outcome measures			
ATQoL (B1)			
Safety	2.2 (1.0)	2.2 (1.1)	9868.50
Control	2.1 (1.1)	1.9 (0.8)	8822.00
Participation	2.5 (1.0)	2.3 (1.1)	8859.00
(5-point Likert scale: 1 = very safe to 5 = very unsafe; similar for Control and Participation)			
EQ-5D (B1)			
Health state Index value (0.0 = very bad to 1.0 = very good)	0.7 (0.2)	0.8 (0.2)	10119.50
Health today (0 = worst health to 100 = best health)	68.9 (18.6)	69.0 (18.9)	9882.00
PIADS (B2)			
Total score short version	0.8 (0.8)	-	-
Competence	0.6 (0.7)	-	-
Adaptability	0.7 (0.8)	-	-
Self-esteem	0.6 (0.6)	-	-
(7-point Likert scale: -3 = very negative to +3 = very positive outcomes)			

*Data in the table are either means (SD) or numbers (%)
**None of the differences was significant (all p>0.05)

In every modeling process, a maximum GLMM was calculated first, with random intercepts as well as random slopes. Since sometimes the group sizes were rather small and unbalanced, the Satterthwaite approximation for the degrees of freedom was chosen. The covariance type for the second level variable was always Variance Components. All analyses were adjusted for multiple comparisons with the sequential Sidak correction. We set the significance threshold at p=0.05. Cohen's d and its respective confidence intervals (CIs) were calculated for the main effects and interactions of categorical variables following the procedures proposed by Feingold (2013, 2015), i.e. using the equation

$$d = (b * \text{duration}) / SD \quad (1)$$

for Group x Time interaction effects, and the equation

$$d = b / SD \quad (2)$$

for all other effects. The duration was calculated by the number of measurement points minus 1, as standard deviation, we used the (pooled) outcome variable SD of IG (and CG) participants at baseline. For effects that involve continuous variables, semi-partial R^2 coefficients would have had to be calculated with special software (Jaeger, Edwards, Das, & Sen, 2017). As this extends the scope of this study, for continuous variables only the unstandardized b-coefficients are reported. All data analyses were conducted in SPSS v27.

Results

Sample characteristics

In total, 281 persons filled in the B1 questionnaire, with substantial attrition between measurement points (*Figure 3*). 31% of all dropouts can be attributed to delays in recruitment, technology installations, and questionnaire administration due to the COVID-19 pandemic. Chi square analyses showed that dropouts between B1 and M6 consisted of significantly more females ($\chi^2(1)=9.69$; p=0.002) and between M6 and M13 of significantly more IG participants than continuers ($\chi^2(1)=15.92$, p<0.001). There was an above-proportion number of Austrians and a below-proportion number of Italians in dropouts compared to continuers both before M6 ($\chi^2(3)=21.35$; p<0.001) and M13 ($\chi^2(3)=25.81$; p<0.001). Dropouts before M6 as well as before M13 had significantly lower health at B1 than continuers (EQ-5D-5L Index value: U=10590.5, p=0.001; U=4835.5, p=0.019; EQ-5D-5L Health today: U=11181.5, p<0.001; U=4800.0, p=0.025).

The average age was 77.2 (SD = 7.9), with a range of 51 to 97 years. The sample was primarily female (69.0%), with more than two-thirds of participants living alone (71.2%). Participants came from both rural and urban areas, and lived in either private homes (76.0%) or assisted living facilities (24.0%). There were no significant differences between the IG and the CG at baseline (*Table 1*).

We followed an intention-to-treat approach – all participants who completed questionnaires at one, several, or all measurement points were included. No cases (e.g., outliers) were excluded. Regarding missing values, the unit non-response

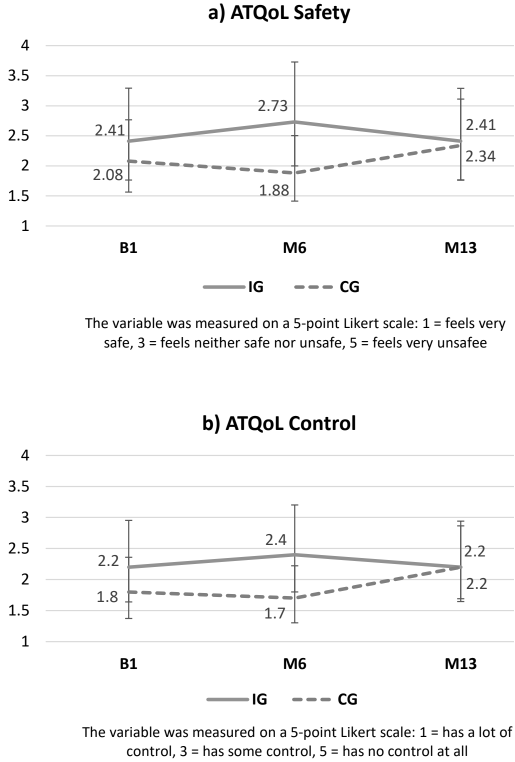

Figure 4. Significant interaction Time x Group for ATQoL Safety and ATQoL Control (adjusted means, all covariates included)

was rather high due to attrition, for PIADS also the item non-response rates were considerable with up to 17%. As we conducted GLMM analyses, which estimate parameters well in case of missing values (Brauer & Curtin, 2018) we did not impute missing data.

During the trial, 8 incidents, like falls, were registered, with mixed feedback about the technology performance in these situations. No missing persons had to be located via the emergency watch.

Impact of the COVID-19 pandemic

The pandemic clearly affected the older persons' perceived participation in enjoyable activities (ATQoL) which had deteriorated significantly in the whole sample at M6 and stayed at that level at M13 ($\chi^2(2)=33.62$, $p<0.001$). Also perceived control decreased slightly between M6 and M13 ($\chi^2(2)=6.25$, $p=0.044$); in contrast, participants' sense of safety did not change significantly. At M6, 43% of the overall participants felt their general QoL was somewhat or much worse than before the pandemic. At M13, it had deteriorated even more ($U=1390.00$, $p<0.001$), and there were no differences between IG and CG. Many participants used technologies for communication, information, and entertainment more during the pandemic at M6 (53%, 34%, and 24% respectively) and at M13 (46%, 41%, and 36%), compared to before the pandemic. Differences between M6 and M13 were not significant; the usage of safety technologies did not change for most participants. During the pandemic, 2 IG participants moved temporarily to live somewhere else, 2 indicated that the pandemic affected how they used the i-evAALution technologies in a negative way, and 11 felt that it changed their use in a positive way.

Reliability analyses

Reliability analysis for the 3-item ATQoL-scale at baseline resulted in an acceptable Cronbach's Alpha of 0.71. The coefficient for the short PIADS total score was very high at 0.94. For the three subscales Competence, Adaptability, and Self-esteem, all coefficients were sufficiently high as well (0.90, 0.89, 0.80). However, the three negative items on confusion, frustration, and embarrassment showed low corrected item-total correlations of under 0.30. Furthermore, the three items led to slight increases in Cronbach's Alpha when deleted, as did the item on well-being. An explanation could be that participants overlooked the negative items due to tiredness or lack of motivation. However, as these increases only are a few percent, we assume that removing the items does not substantially change the (sub)scales. In a recent systematic review, Atigossou, Honado, Routhier, and Flamand (2021) state that so far not many studies have investigated the psychometric properties of PIADS; thus, future research seems indicated. For the EQ-5D-5L, internal consistency is not an appropriate measure (Feng, Kohlmann, Janssen, & Buchholz, 2021). We therefore calculated Intraclass Correlation Coefficients (ICC) to estimate the test-retest reliability for B1 and M6 measurements – for the EQ-5D-5L Index value the ICC was 0.83, and for the Health today measure 0.72.

Impact of the technology use on primary outcomes

In the GLMMs, model convergence could not be achieved when all or even one random slope (e.g., of the interaction effect) was included. Therefore, all models below contain a random intercept only, which in most analyses showed significant variance across the test persons (we report details only if it did not).

H1a: QoL-effects due to technology use over 6 months

All statistical parameters for H1 results are displayed in *Table 2*, numbers in the text indicate the rows in the table. We found that, contrary to our hypothesis, the IG participants' feeling of safety decreased over time whereas that of the CG participants increased (1), that older participants had lower feelings of safety than younger participants (2), and that participants with low

Table 2 Results for H1a and H1b (groups: IG vs. CG)

No.	Effect	b	SE	(df) t	p	CI lower	CI upper	d	CI lower	CI upper
				ATQoL Safety, B1-M6						
(1)	Interaction Time x Group	-0.17	0.07	(144) -2.50	0.013	-0.31	-0.04	-0.18	-0.31	-0.04
(2)	Age	0.01	0.005	(128) 2.36	0.020	0.002	0.02	-	-	-
(3)	Education	0.33	0.12	(128) 2.67	0.009	0.09	0.57	0.33	0.09	0.57
				ATQoL Safety, B1-M6-M13						
(4)	Interaction	-0.22	0.10	(190) -2.23	0.027	-0.42	-0.03	-0.43	-0.82	-0.05
	Time x Group	-0.34	0.10	(190) -3.45	0.001	-0.54	-0.15	-0.67	-1.05	-0.29
				ATQoL Control, B1-M6						
(5)	Main effect Group	-0.28	0.08	(126) -3.64	<0.001	-0.44	-0.13	-0.31	-0.47	-0.14
(6)	Age	0.01	0.004	(125) 2.44	0.016	0.002	0.02	-	-	-
				ATQoL Control, B1-M6-M13						
(7)	Interaction	-0.18	0.09	(188) -1.98	0.049	-0.37	-0.001	-0.42	-0.84	-0.002
	Time x Group	-0.32	0.09	(188) -3.51	0.001	-0.51	-0.14	-0.74	-1.15	-0.32
(8)	Age	0.01	0.01	(70) 2.09	0.040	0.001	0.03	-	-	-
				ATQoL Participation, B1-M6						
(9)	Main effect Time	0.17	0.06	(149) 2.95	0.004	0.06	0.29	0.16	0.05	0.27
(10)	QoL impact of pandemic	0.12	0.004	(141) 2.89	0.005	0.04	0.20	-	-	-
				ATQoL Participation, B1-M6-M13						
(11)	Main effect Time	0.26	0.08	(198) 3.16	0.002	0.10	0.42	0.26	0.10	0.42
		0.25	0.08	(198) 2.99	0.003	0.08	0.41	0.25	0.08	0.41
(12)	Age	0.01	0.005	(91) 2.18	0.032	0.001	0.02	-	-	-
(13)	Economic situation	0.22	0.07	(91) 2.91	0.005	0.07	0.37	0.22	0.07	0.37
(14)	QoL impact of pandemic	0.10	0.04	(91) 2.68	0.009	0.03	0.18	-	-	-
				EQ-5D-5L Index value, B1-M6						
(15)	Age	0.003	0.001	(126) 2.74	0.007	0.001	0.01	-	-	-
(16)	Use of communication technologies	0.06	0.02	(125) 2.67	0.009	0.02	0.11	0.36	0.09	0.62
				EQ-5D-5L Index value, B1-M6-M13						
(17)	Main effect Time	-0.05	0.01	(198) -4.14	<0.001	-0.08	-0.03	-0.35	-0.52	-0.18
		-0.03	0.01	(198) -2.47	0.014	-0.06	-0.01	-0.21	-0.37	-0.04
(18)	Age	0.003	0.002	(91) 2.25	0.027	0.000	0.01	-	-	-
				EQ-5D-5L Index value, B1-M6						
(19)	Age	0.02	0.004	(141) 3.35	0.001	0.01	0.02	-	-	-

education perceived less safety than those with high education (3). CG participants perceived more control than IG participants (5), and older persons felt less control than younger ones (6). The perceived participation declined overall from B1 to M6 (9), additionally, those with a deterioration in QoL due to the pandemic perceived less participation (10).

Both the Index value and the Health today value were recoded to convert the negatively skewed distributions to positively skewed and thus fit gamma distributions with log links in the analyses. Hence, contrary to the original values, smaller numbers indicate better and larger numbers indicate worse health-related QoL on both variables. For the EQ-5D-5L Index value, older participants perceived their health-related QoL as being worse than younger ones (15), and persons who used more communication technologies during the pandemic than before perceived a better health-related QoL than persons who still used them in the same way (16). Due to the overdispersion of the EQ-5D-5L Health today data, we computed every analysis assuming a gamma distribution as well as a negative binomial distribution to check which fit the data better. Only one model with gamma distribution and log link reached significance. It indicated that older participants again perceived lower health than younger people (19).

H1b: QoL-effects due to technology use over 13 months

For ATQoL Safety, an interaction effect contrary to our hypothesis between B1 and M6, and concordant to our hypothesis between M6 and M13 emerged (4) (*Figure 4a*). For ATQoL Control, the same interaction effect and pattern between the three measurement points appeared (7) (*Figure 4b*). Older people perceived less control than younger ones (8). There was a general decline of participation between B1 and M6, as well as between B1 and M13 (11), older persons perceived less participation than younger ones (12), persons with a difficult economic situation perceived less participation than those with better economic situation (13), as did those who experienced a strong negative impact of the pandemic on QoL at M13 (14). Regarding the EQ-5D-5L Index value, the health-related QoL had deteriorated significantly at M13 compared to B1 and M6 (17), and

Table 3. Results for H2a and H2b

No.	Effect	b	SE	(df) t	p	CI lower	CI upper	d	CI lower	CI upper
				Short PIADS total score, B2-M6						
(20)	Main effect Time	-0.07	0.02	(83) -3.53	0.001	-0.11	-0.03	-0.08	-0.13	-0.04
				Short PIADS total score, B2-M6-M13						
(21)	Main effect Time	-0.07	0.02	(127) -3.80	<0.001	-0.11	-0.04	-0.08	-0.12	-0.04
		0.07	0.03	(127) 2.54	0.012	0.01	0.12	0.07	0.01	0.12
				PIADS Adaptability, B2-M6-M13						
(22)	Main effect Time	0.08	0.03	(116) 2.64	0.009	0.02	0.14	0.08	0.02	0.14
				PIADS Self-esteem, B2-M6						
(23)	Main effect Time	-0.05	0.02	(66) -2.87	0.005	-0.08	-0.02	-0.08	-0.13	-0.02
				PIADS Self-esteem, B2-M6-M13						
(24)	Age	-0.02	0.004	(28) -3.46	0.002	-0.02	-0.01	-	-	-

age had a negative effect (18).

Summary for H1a and b

Overall, for the outcome variables Safety and Control, at M6 the CG participants had more positive perceptions than the IG participants, even though at B1 there were no significant differences between the two groups (*Table 2*). However, towards M13, a trend in line with our hypotheses emerged, with IG participants showing feelings of safety and control similar to those at B1, and CG participants perceiving decreased feelings. Participation declined for all participants over the course of the study. We could not confirm H1a and b for either the EQ-5D-5L Index value or the Health today measure. Only negative effects of time, age, and perceived economic situation emerged, which are all independent of our technology intervention.

H2a: Psychosocial effects on the IG participants due to technology use over 6 months

The distributions of the short PIADS total score as well as the different subscales were close to normal, with a positive skew for some. Therefore, we calculated every GLMM first assuming a linear model with identity link and then a gamma distribution with log link, which in general had substantially lower AICCs. Here, we report the effects of the models with gamma distributions. All statistical parameters for H2 results are listed in *Table 3*. Regarding the short PIADS total score, IG participants expected a higher psychosocial impact at B2 compared to the experienced impact at M6 (20). For the subscales of Competence and Adaptability, no significant effects could be detected. For Self-esteem, again the perceived impact of the technologies decreased between the two measurement points (23).

H2b: Psychosocial effects on the IG participants due to technology use over 13 months

Regarding the short PIADS total score, again there was a decrease in impact from B2 to M6, but an increase from M6 to M13, with the impact at M13 reaching about the slightly positive expectation from B2 (21). Over 13 months, we found a significant increase in perceived adaptability from M6 to M13 (22). For the subscale Competence, no effects could be detected. Older participants perceived less self-esteem impact than younger ones (24).

Summary for H2a and b

In summary, for PIADS the expectations of the impact of technology use were higher at B2 than the perceived impact after the actual use at M6 (*Table 3*). However, for the participants who remained in the trial for the whole duration, a positive development was demonstrated for Adaptability and the short PIADS total score, with the perceived impact increasing between M6 and M13, approximately reaching the initial expectations.

H3a: QoL- and psychosocial effects on the IG participants due to frequency of technology use over 6 months

Neither for the three ATQoL constructs nor the EQ-5D-5L Index value and Health today measure, the hypothesis that more frequent use of the emergency watch or tablet would lead to more favorable outcomes was confirmed. For the PIADS (sub) scales, some effects of the emergency watch could be found; the respective statistical parameters are listed in *Table 4*. Regarding short PIADS, the overall impact was more positive for participants who used the emergency watch more frequently at M6 (subjective measure) than for those who used it less (25), and for participants who generally used more or at least the same amount of safety technologies during the pandemic vs. less (26). Furthermore, there was a negative influence of deteriorated QoL due to the pandemic (27), the model had no significant variance in intercepts, Var(Intercept)=0.01, SE=0.004, p=0.116. Furthermore, frequent users of the emergency watch (objective and subjective measure) perceived more competence than rare users (32, 33). In the model for the subjective frequency of use, there was no significant variance in intercepts, Var(Intercept)=0.001, SE=0.004, p=0.744. Regarding Self-esteem, for the subjective measure, again a positive main effect of frequency of use emerged (34) and the intercepts did not vary significantly, Var(Intercept)=0.01, SE=0.003, p=0.085.

Table 4. Results for H3a and H3b (groups: frequent vs. rare users of the emergency watch)

No.	Effect	b	SE	(df) t	p	CI lower	CI upper	d	CI lower	CI upper
					Short PIADS total score, B2-M6					
(25)	Main effect Group	-0.10	0.04	(47) -2.28	0.025	-0.19	-0.01	-0.12	-0.22	-0.02
(26)	Use of safety technologies	0.42 0.36	0.15 0.13	(47) 2.84 (47) 2.84	0.007 0.007	0.12 0.10	0.72 0.61	0.49 0.42	0.14 0.12	0.84 0.71
(27)	QoL impact of pandemic	-0.06	0.03	(45) -2.14	0.038	-0.11	-0.003	-	-	-
					Short PIADS total score, B2-M6-M13					
(28)	Main effect Group	-0.49	0.17	(7) -2.83	0.015	-0.86	-0.11	-0.50	-0.88	-0.12
(29)	Age	-0.02	0.01	(7) -3.61	0.007	-0.03	-0.01	-	-	-
(30)	Economic situation	0.93	0.27	(7) 3.40	0.011	0.28	1.57	0.95	0.29	1.61
					PIADS Adaptability, B2-M6-M13					
(31)	Main effect Group	-0.12	0.06	(96) -2.05	0.042	-0.24	-0.004	-0.12	-0.24	-0.004
					PIADS Competence, B2-M6					
(32)	Main effect Group	-0.10	0.04	(76) -2.44	0.016	-0.18	-0.02	-0.13	-0.23	-0.03
(33)	Main effect Group	-0.15	0.05	(35) -2.79	0.007	-0.25	-0.04	-0.20	-0.34	-0.06
					PIADS Self-esteem, B2-M6					
(34)	Main effect Group	-0.10	0.04	(36) -2.38	0.021	-0.19	-0.02	-0.16	-0.30	-0.03
					PIADS Self-esteem, B2-M6-M13					
(35)	Main effect Time	-0.05 0.05	0.02 0.02	(107) -2.06 (107) 2.02	0.042 0.046	-0.09 0.001	-0.002 0.10	-0.06 0.06	-0.12 0.002	-0.001 0.11

H3b: QoL- and psychosocial effects on the IG participants due to frequency of technology use over 13 months

Also regarding H3b, only for the PIADS (sub) scales and the use of the emergency watch, significant effects could be found. For short PIADS, again people who used the emergency watch more frequently at M6 (subjective measure), had a higher total score than people who used it less (28), older participants perceived a less positive impact than younger ones (29), and persons who felt they lived in a comfortable economic situation showed higher scores than persons who felt they had difficulties to get by (30); the intercepts did not vary significantly, Var(Intercept)=0.001, SE=0.004, p=0.769. Furthermore, persons who used the emergency watch frequently (objective measure) perceived higher adaptability than the persons who used it rarely (31). There was an overall decrease in self-esteem impact (objective measure) between B2 and M6, but an increase between M6 and M13 (35).

Summary for H3a and b

Overall, in line with our hypothesis, participants who used the emergency watch frequently experienced more positive outcomes for most PIADS (sub)scales than those who used it rarely (*Table 4)*. Regarding frequent vs. rare tablet use (objective measure), only for short PIADS negative main effects Time emerged – the outcome was more positive at baseline than at M6, which is in line with some results found when comparing IG and CG (H1a and b).

Discussion

The present study examined different QoL-effects of using a bundle of aging-in-place technologies for up to 13 months in four European countries. It addressed the still-existing evidence gap for long-term effects of technology use on older people and gives new insights about different QoL outcomes. Concerning H1a and b, we found that the beneficial effects of technology use rather consisted in the stabilization of perceived safety and control towards M13, an actual increase could not be verified. During the first 6 months, the IG participants perceived less safety and control than the CG participants, which could be an effect of disappointment about the technologies – also the PIADS results show that expectations were often higher than the actual perceived technology impact. Perceived participation on the other hand declined over time for all test persons, an effect that we attribute to the contact restriction measures during the COVID-19 pandemic. The analyses showed that participation was negatively influenced by the pandemic impacts on QoL as well as chronological age and economic situation, which is in line with previous research (Cruice, Worrall, & Hickson, 2005; Curvers, Pavlova, Hajema, Groot, & Angeli, 2018; Gallo, Marshall, Levy-Storms, Wilber, & Loukaitou-Sideris, 2022). The significant effects for the ATQoL measures can be classified as mostly low, the interaction effect sizes for all three measurement points were higher due to the consideration of multiple measurements (see Equation 1). Regarding our general health-related outcomes, for the EQ-5D-5L Index value, a deterioration in all participants was observed after 13 months (effect sizes were rather small), probably due to a general health decline in older people over time, which was also found in previous RCTs (Hirani et al., 2014; Mann et al., 1999). For the EQ-5D-5L Health today measure, only a negative influence of age emerged. We conclude that the EQ-5D-5L was too generic to capture effects caused by our technology bundle – or the effects were so small they were masked by adverse age-related health changes. This is in line with other RCTs which were not able to demonstrate general beneficial impacts of technology use (Gustafson et al., 2021; Morgenstern et al., 2015). Overall, H1a was not confirmed, and H1b was partly confirmed. Interestingly, the use of more communication technologies during the pandemic was related to a better EQ-5D-5L Index value – either participants with better health used communication technologies more (see Wan, Lighthall, & Paulson, 2021) or the use of technologies helped them feel subjectively healthier (see Hartanto et al., 2020).

Concerning the specific effects of technology use on IG participants (H2a and b), measured with PIADS, expectations about the potential impact were higher than actual perceptions after using them for 6 months. Technology acceptance research suggests that expectations about technology performance, but also about executing a desired behavior with the help of technology, play a role in its adoption (Maruping, Bala, Venkatesh, & Brown, 2017; Venkatesh, Brown, Maruping, & Bala, 2008). It is therefore reasonable to assume that older persons who were interested in participating in our study had relatively high expectations about our bundle. However, different technological problems during the trial (see Limitations) might have attenuated the actual benefits. Some of our results are contrary to what was found by Czaja et al. (2018): they explained their observation that positive technology effects at 6 months disappeared again at 12 months with a novelty effect that wears off over time. In our study, however, participants initially seemed to experience some disappointment with what our technologies could deliver. Yet, for persons who stayed in the trial for 13 months, this phase was overcome, and participants reported positive impacts on adaptability, and overall (short PIADS total score), in line with their initial expectations. We can thus regard H2b as partly confirmed, whereas H2a could not be verified. The standardized effect sizes for the change of the outcomes over time were very low. Regarding the rates of item non-response for PIADS, our results differ from previous studies, which did not find any problems in this regard for middle-aged patients (Fundarò et al., 2018) and when administrating the questionnaire via interview (Wiklund Axelsson & Melander Wikman, 2016). This leads to the conclusion that the scale might be less suitable for self-administration in older persons.

Both H3a and b were partly confirmed. Results revealed that frequent use of the emergency watch was more beneficial than frequent use of the tablet – there were significant main effects for all PIADS (sub)scales when comparing participants who used the watch frequently vs. rarely. The effects were more pronounced when analyzing the data of persons who participated for 13 months, with rare users perceiving the emergency watch more negatively and frequent users perceiving it more positively than the two groups at M6. Standardized effect sizes were mostly small to medium.

Regarding the meaningfulness of the results, our effect sizes were mostly small to medium in size. This is in line with previous RCTs, where reported effect sizes can mostly be classified as small (Hedge's g or Cohen's d around .20, Cohen's f around .25; Cohen, 1988) and seems evident when considering the range of extrinsic and intrinsic factors contributing to QoL-domains like health or social support (Wiggins, Higgs, Hyde, & Blane, 2004). Overall, the results for the specific QoL scales ATQoL and PIADS indicate that there are positive effects of the i-evAALution technologies after long-term use, whereas, during the first 6 months of the study, there were also several results contrary to our hypotheses. This could be explained by overcoming technology disappointment, the assumption that for some technologies beneficial impacts only emerge after a certain period of usage, or by the fact that the participants who remained in the trial for 13 months profited more from the technologies, maybe because they perceived their health being better than the M6 sample. This positive relationship between health and technology use was also reported by others (Wan et al., 2021). Furthermore, we showed that effects on the outcomes can rarely be attributed to increased use of everyday technologies for communication, information, and entertainment during the pandemic, as these covariates had little effect on the models.

In this section, we would also like to discuss some aspects of designing aging-in-place technologies. To ensure technology accessibility and acceptance as much as possible, many researchers have emphasized that older adults should be involved in the technology development, in order to ensure its design is user-centered (Franz & Neves, 2019; Mannheim et al., 2019; Wang et al., 2019). This also means responding to individual differences on factors like socio-economic status, cultural background, literacy, or functional status in the very heterogenous group of older people (Czaja, Boot, Charness, & Rogers, 2019). Others have stressed that no one should be marginalized, regardless of capabilities or disabilities, i.e., that (technological) products should have an inclusive design (Langdon, Lazar, Heylighen, & Dong, 2014). Primary users of technologies in the home and care context are mostly older people, but also the expertise of care staff can be important when aiming to develop helpful and easy-to-use technologies (Fritz & Dermody, 2019). Others have highlighted the importance of "good universal design [which] benefits everyone" (Czaja et al., 2019, p.65) – in fact, all design approaches mentioned above have one thing in common: the highest possible accessibility of technology for as many purposes as possible, thus being universal (Persson, Åhman, Yngling, & Gulliksen, 2015).

A different design principle is a sustainable design, which incorporates "larger environmental, resource, and social issues into decisions of the conceptualization, design, manufacture, operation, and end-of-life of products and systems" (Tate et al., 2010, p.418). A comprehensive overview was given by Kuijer (2014) who also describes some examples from the area of household technologies and the potential they hold for smart interactions which lead to their sustainable functioning and use. Others have summarized how different technologies in areas relevant to older people, like eHealth, activities of daily living and well-being, contribute to sustainability, and which challenges for developers still exist (Morato, Sanchez-Cuadrado, Iglesias, Campillo, & Fernández-Panadero, 2021).

One main part of our i-evAALution technology bundle was designed in a thorough user-centered process with extensive iterative testing and improving: The emergency watch was developed during the European project Personal Protection and Caring System (2PCS) (Call AAL-2010-3 of the AAL Programme), involving older people and professional carers in 5 European countries. The off-the-shelf smart home technologies mostly consisted of passive devices with very few interaction possibilities, hence, design issues are only marginally relevant. We acknowledge that the tablet and the final technology bundle could have been improved by involving user-centered design principles more and thus adapting it even more to the actual needs of the target group. On the other hand, we argue that our technologies consider several sustainable design principles. First, the bundle was developed in a way to allow different smart home and AAL-technologies to be removed or integrated, so a long-term and sustainable use according to the (changing) needs of the aging individual could be ensured (Peek et al., 2019). Furthermore, smart functionalities like smart lighting at night are energy-efficient and thus sustainable. From the resource perspective, family members, who would otherwise spend more time checking on (and worrying about) their loved ones, are only alerted in critical situations or real emergencies.

Limitations

Some limitations regarding our study must be reported. First, the baseline levels of our primary outcome variables were relatively high, which probably made it difficult to evoke further improvements. This could be explained by self-selection effects, i.e., only persons with relatively high levels of functioning were reached through recruitment activities, and had the physical, psychological, and cognitive resources to participate in a scientific study (Bieg et al., 2022; Gustafson et al., 2021). Furthermore, the well-being paradox might have contributed to high initial QoL levels; it describes an often observed discrepancy between unfavorable objective QoL factors and rather favorable subjective perceptions by older people, especially the young-old (Hansen, 2020). Additionally, a multiple-choice question at B1 about motivations to participate revealed that 66% of the older persons had decided to join because they felt technologies like the ones in the study will be important in the future for older people in general. Motivations that indicate concrete needs or expectations about personal beneficial effects of the technologies were indicated less (by 33%-53% of the participants).

Due to the COVID-19 pandemic, it was difficult to provide thorough technology training according to the participants' needs, and adequate help when technology problems occurred – both of which probably prevented participants to tap the full potential of the bundle's functionalities, even though the subjective perceptions of preparedness for the technology use by the training, assessed at B2, were rather high. Technological limitations, in that not all functionalities could be provided for all older participants and not all bundle components were functioning adequately, probably reduced the potential of the technologies to improve QoL further (also see Kristoffersson et al., 2019). These problems are reflected in the number of participants who indicated they dropped out due to dissatisfaction with the technologies or lost interest (15% of the IG participants). Again, the remaining IG participants, especially at M13, can thus be regarded as more motivated and satisfied with the technologies, which probably led to positive trends toward M13.

From a methodical point of view, we assume that our analyses were underpowered due to an insufficient number of participants, and thus the ability to detect effects was limited, especially for the analyses that only include IG participants – the group sizes here were partly very small and unbalanced. Furthermore, in none of the models was it possible to include random slopes due to non-convergence. We thus missed one of the advantages of GLMMs, which is accounting for the variability of individual differences in outcomes over time.

In general, field studies like ours have high external validity, and our technology bundle can be regarded as an example of aging-in-place technologies which will likely be used in many households of older people in the near future. Also by measuring most of the QoL-related constructs with several items, we can assume that our results have at least some generalizability – yet again, power was probably at least partly "traded off" in return (Brauer & Curtin, 2018). Several factors limit the generalizability of our results to the older population of middle European countries: our sample was highly functioning and resourceful, with many dropouts having less motivation (17% of the CG participants dropped out due to dissatisfaction with being in the CG, lost interest, or reluctance to fill in the questionnaires) and poorer health. Furthermore, we were not able to carry out random sampling.

Conclusions

Even though the onset of the COVID-19 pandemic affected our RCT both in its organization and in the technology impacts on QoL, we were able to demonstrate some positive effects. Furthermore, by including covariates on the impacts of the pandemic on QoL and everyday technology use, we could illustrate its effects in addition to the original scope of the study. Our results show that in future studies it will be important to use measures that are very specific to the effects that aging-in-place technologies are able to provoke, which is in line with many previous studies. However, even in the light of powerful external influences on QoL, like pandemics or individual age-related losses in social and health domains, in our opinion evidence is building that technologies do have the potential to mitigate adverse developments in old age (also see Czaja, 2016). The i-evAALution trial results add important insights to what was documented by other RCTs in the field and could contribute to future meta-analyses which consolidate previous effects to draw more comprehensive conclusions about the benefits of the long-term use of aging-in-place technologies.

To unfold the beneficial effects of aging-in-place technologies as much as possible in the real world, the housing context of older people has to be kept in mind. Researchers from the area of environmental gerontology have stressed the need for the congruence between an older person's environment and individual characteristics, which an older person reaches by either adapting to the environment or by altering it (Lawton, 1990; Lawton & Nahemow, 1973). Hence, if studies indicate that aging-in-place technologies have a positive impact and it comes to the actual implementation in older persons' homes, they not only have to be adapted to the individual's needs and level of functionality and competences, but they also need to be integrated well into the living environment (Iwarsson, Horstmann, Carlsson, Oswald, & Wahl, 2009). The technology bundle of the present study was designed and compiled with the aim of fulfilling exactly these requirements.

When adapting the home of a frail older person, several aspects have to be considered. Before equipping it with digital technologies, architectural barriers should be removed to ensure a safe and comfortable environment for both the older person and the carer (Pettersson, Malmqvist, Gromark, & Wijk, 2020). Furthermore, even today it is difficult for older people to get information about aging-in-place technologies, i.e. their characteristics, benefits, costs, etc. (Betts, Hill, & Gardner, 2019; Seifert & Rössel, 2021). Not only well-structured and up-to-date online information platforms should be available, but also low-level, easily accessible information helpdesks on the municipal level, especially in rural areas. Ideally, these helpdesks should be integrated into care and assistance processes like case management. Living in old age should be tackled in a wholistic way (Rogers, Ramadhani, & Harris, 2020) and be centered around finding the most appropriate housing and care arrangements for an individual, from removing architectural barriers in an existing flat up to finding the most helpful technologies to address concrete everyday challenges of the older person (Fausset et al., 2011; Kelly, Fausset, Rogers, & Fisk, 2014). Useful scientifically developed tools are available for this (Iwarsson, Slaug, & Fänge, 2012; Ullrich et al., 2022).

Even though empirical results about the beneficial effects of technologies on QoL still don't paint a distinct picture, in the long run, the care sector will benefit from this research. Especially in a time when staff and places in residential care facilities are scarce and living at home as long as possible could contribute to saving costs for the public sector but also for the older person (Finch, Griffin, & Pacala, 2017; Social Protection Committee and the European Commission, 2021; Tappenden, Campbell, Rawdin, Wong, & Kalita, 2012). In the future, public health and care administrations will have to evaluate the possibility to hand over low-qualified and routine care tasks to technologies, in order to save scarce human resources for relationship-oriented and qualified care (Zigante, 2020). In summary, politics, the private and public housing sector, and every older person together with their family members have to assume responsibility to ensure the level of QoL that older people desire (Bosch-Farré et al., 2020; Pettersson et al., 2020) – living at home with and without technologies.

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Appendix A: List of abbreviations

General terms
AAL: Active Assisted Living
IADL: Instrumental Activities of Daily Living
QoL: Quality of Life

Methodology
RCT: Randomized Controlled Trial
CG: Control Group
IG: Intervention Group
B1: Baseline 1 measurement
B2: Baseline 2 measurement
M6: Follow-up measurement after 6 months
M13: Follow-up measurement after 13 months

Measurement instruments
MMSE: Mini Mental State Examination
ATQoL: Assistive Technologies Qualitiy of Life scale
PIADS: Psychosocial Impacts of Assistive Devices Scale
EQ-5D-5L: EuroQoL 5 dimensions, 5 levels scale

Appendix B – Functionalities of the i-evAALution technology bundle

1. Managing appointments and tasks on the tablet calendar
2. Making service calls via the emergency watch to a professional care provider or a reference person
3. Using a local information website for older people on the tablet
4. Switching lights connected by smart plugs on or off with a smart mobile switch, a button on the tablet or passively with a movement sensor
5. Playing games on the tablet
6. Triggering an emergency alarm by pressing the button on the tablet, the button on the emergency watch, or the stationary alarm button
7. Locating the test person, who wears the emergency watch, via GPS if the reference person suspects he or she is missing
8. Automatic fall detection and alarm forwarding to the reference person or an emergency call center by the emergency watch
9. Email notification of the reference person if no movement of the test person in his / her home was detected in a predefined time span (e.g., 7:00 to 18:00)
10. Email notification of the reference person if a door equipped with a sensor was not opened before a predefined time in the morning (e.g., 9:00)
11. E-mail notification of the reference person if the alarm of the smoke detector was triggered