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Digital behavior change interventions to promote physical activity and/or reduce sedentary behavior in older adults: a systematic review and meta-analysis.

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Abstract

Background: Physical activity and sedentary behavior are modifiable risk factors for non-communicable disease and healthy ageing, however the majority of older adults remain insufficiently active. Digital behavior change interventions (DBCI) have the potential to reach many older adults to promote physical activity and reduce sedentary time. This study aims to assess the efficacy of DBCI interventions in older adults (≥ 50 years) on physical activity and sedentary behavior.

Methods: A systematic review of major databases from inception to 03/2018 was undertaken. Randomized controlled trials (RCT) or pre-post interventions assessing effects of DBCI on physical activity and/or sedentary behavior in older adults (≥50 years) were included. Random effects meta-analyses were carried out.

Results: Twenty-two studies were included, including 1757 older adults (mean age=67 years, %male=41), 68% showed moderate-high risk of bias. Meta-analyses suggested that DBCI increased total physical activity among RCT studies (n = 8) (SMD=0.28; 95%CI 0.01, 0.56; p=0.04) and pre-post studies (n = 6) (SMD=0.25; 95%CI 0.09, 0.41; p=0.002), increased moderate-to-vigorous physical activity (SMD=0.47; 95%CI 0.32, 0.62, p<0.001; MD=52min/week) and reduced sedentary time (SMD=-0.45; 95%CI -0.69, -0.19; p<0.001; MD=58min/day). Reductions in systolic blood pressure (-11bpm; p=0.04) and improvements in physical functioning (p=0.03) were also observed.

Conclusions: DBCI may increase physical activity and physical functioning, and reduce sedentary time and systolic blood pressure in older adults, however more high-quality studies are required.

Keywords: Digital behavior change intervention; older adult; physical activity; sedentary behavior.

1. Introduction

Older adults (age ≥ 50 years) comprise approximately 35% of the population in the United States of America (USA) (Statistica, 2018) and 40% of Europe (Eurostat, 2018), and the proportion of older adults is projected to continue to increase (Office for National Statistics, 2017). Despite people today living longer than their predecessors, quality of life and health are not guaranteed to be better (Beard et al., 2016) and many are living more years with disability (James et al., 2018). In order to complete everyday tasks such as climbing stairs, many older adults function close to their maximum capacity, meaning that further decline or physical setback could increase their risk of falling and/or becoming dependent on carers (Deandrea et al., 2010; Rikli, 1999). Non-communicable diseases (NCDs), such as cardiovascular disease, diabetes, certain cancers and chronic respiratory diseases, are the leading cause of death in older age globally (Beard et al., 2016) and also impact quality of life (QoL) and ability to live independently (Sazlina et al., 2012).

Low levels of physical activity (PA) and excessive sedentary behavior (SB) are independently associated with multiple NCDs in older adults (Chad et al., 2005; Wirth et al., 2017). For instance, lower levels of PA have been shown to be associated with musculoskeletal, respiratory, heart, circulatory, digestive and kidney/bladder/urinary conditions (Chad et al., 2005). Moreover, higher levels of PA are associated with healthy ageing (Daskalopoulou et al., 2017) and are protective against aging-related decline in physical function (Tak et al., 2013). A systematic review found positive correlations between SB and body mass index (BMI), fat mass, cholesterol and insulin levels in older adults (Wirth et al., 2017). Therefore, regular and sustained engagement in PA and reduction in SB has the potential to improve health, QoL and independence in older adults (Chad et al., 2005; Daskalopoulou et al., 2017; Smith et al., 2015; Tak et al., 2013) and are influential in the prevention and/or management of NCDs (Global Advocacy for Physical Activity (GAPA) and the Advocacy Council of the International Society for Physical Activity and Health (ISPAH), 2012).

Despite these benefits, a large proportion of older adults fail to meet recommendations for PA. In the USA, the prevalence of older adults doing no activity beyond baseline activities of daily living was 25.4% (95% confidence interval [CI] 25 - 25.9) in older adults aged 50-64 years, 26.9% (95% CI 26.3 – 27.5) in those aged 65-74 years and 35.3% (95% CI 34.5 – 36.1) in those aged ≥ 75 years old (Watson et al., 2016). Across Europe, one in eight older adults ≥ 55 years (12.5%) were categorized as having low levels of PA (defined as never or almost never engaging in moderate-to-vigorous physical activity (MVPA)) (Gomes et al., 2017). A systematic review showed that 67% of older adults aged ≥60 years spend ≥8.5 hours per day sitting when objectively measured (Harvey et al., 2013). A cross-sectional study in Scotland found older adults ≥ 65 years old spend an average of 59.2% of their day in SB (range 28.3% - 94%), averaging 14.2 hours/day (Leask et al., 2015).

Interventions to promote sustainable PA and reduce SB in older adults have achieved limited success particularly over the long term (Chase, 2013; Daskalopoulou et al., 2017; van der Bij et al., 2002). For example, older adults in a 12-week exercise program (functional task exercise group or resistance strength exercise group) showed no significant difference in "change physical activity scores" from the control group at 3, 6 or 9 months (de Vreede et al.,

2007). Another study in older adults who took part in 16 weeks of flexibility training and 16 weeks of resistance training showed no significant difference in PA compared to the control group at the end of the intervention ($p = 0.601$) or at 12 month follow-up ($p = 0.447$) (Bird et al., 2011). Traditional face-to-face approaches promoting health behaviors are typically resource intensive, time-limited, require participants to travel to specific locations and lack appropriate techniques for monitoring daily fluctuations in health behaviors (Hekler et al., 2011). In addition, behavior change interventions require professional expertise in delivering behavior change techniques (BCTs) (Lyons et al., 2014). Thus, there is a need for potentially scalable, low cost and less staff intensive interventions to help address the low levels of PA and high SB in older adults.

Digital behavior change interventions (DBCI) use technologies such as mobile applications (apps) and websites to remotely deliver behavior change interventions (Roberts et al., 2017). DBCI have previously been used in the promotion of PA participation and dietary behaviors (Flores Mateo et al., 2015; Middelweerd et al., 2014; Rabin et al., 2011), rehabilitation programs (Rawstorn et al., 2016), medication adherence (Mistry et al., 2015), management of long-term conditions (Jackson et al., 2016; Su et al., 2016; Vinding et al., 2016) and promoting smoking cessation (Spohr et al., 2015; Taylor et al., 2017; Whittaker et al., 2016). DBCI have previously been used by older adults and are deemed relevant and acceptable for use in this population (Kim and Glanz, 2013; Kolt et al., 2007; Martinson et al., 2010).

Despite this, the overall efficacy of using DBCI to improve health outcomes in older adults has yet to be established. This is an important question, since DBCIs present a novel and scalable approach towards providing tailored behavior change interventions (Forberger et al., 2017; King et al., 2013; Roberts et al., 2017), even for isolated older adults who have limited contact with traditional person(s) or print based PA interventions (Norman et al., 2007), reducing costs and improving patient experience and outcomes (Michie et al., 2017). To our knowledge, no systematic review or meta-analysis has assessed the efficacy of DBCI interventions targeting PA and/or SB in older adults (≥ 50 years) from the general population. Therefore, we conducted a systematic review and meta-analysis with the aim of assessing the efficacy of DBCI interventions in older adults (≥ 50 years) on PA and SB. Secondary aims were to explore any effects of DBCI on physical health, mental health and social outcomes, and explore the theoretical underpinning of studies included.

2. Methods

The following systematic review followed the PRISMA guidelines (Moher et al., 2009). Details of the full protocol for this systematic review were registered on PROSPERO (protocol number: CRD42018090359).

2.1. Search strategy

Electronic databases were searched via OVID from inception to 2nd March 2018 including MEDLINE, PsycINFO and EMBASE. Grey literature was searched manually by entering terms into internet search engines Google and Bing on 2nd March 2018. Searching methodology included terms and synonyms relating to PA, SB, older adults and DBCI (see appendix A). Results of the searches were included in a bibliographic database and duplicates removed. Titles and abstracts of the studies retrieved using the search strategy were screened for inclusion in the systematic review by two screeners independently. The full-text of all potentially eligible papers was reviewed (SS and research assistant) before making a final decision on eligibility. Any discrepancies were discussed until a decision was reached. A third senior reviewer (LS) acted as an adjudicator if a decision was not reached.

2.2. Study inclusion and exclusion

Studies were included if they met the following criteria: (i) randomized controlled trials (RCTs) and pre and post-test studies (ii) in older adults (aged 50+ years) (iii) that use digital interventions (iv) to promote PA and/or reduce SB (v) in any setting. In addition, studies had to be published in an electronic journal article and written in English. PA was defined as any bodily movement produced by skeletal muscles that results in energy expenditure (Caspersen et al., 1985). SB was defined as any waking behavior characterized by an energy expenditure of ≤ 1.5 Metabolic Equivalents (METs) whilst in a sitting or reclining posture (Tremblay et al., 2017). DBCI were defined as devices and programs using digital technology to foster or support behavior change (Yardley et al., 2016), which include but are not limited to websites, mobile phones, smartphone applications (apps), wearable devices, video games, virtual and augmented reality devices. Randomized/controlled clinical trials that used any control condition (e.g. vs. usual care, treatment as usual or non-digital behavior change interventions) and pre and post-test studies versus no control group were included. Studies were excluded if they were observational research including cross-sectional and cohort studies, case studies, case series and qualitative research, were conference abstracts, protocol papers, or N of 1 studies, if participants were not exclusively all aged ≥50, if participants were not directly involved in using the DBCI, if the intervention did not use a digital intervention, or did not have PA/SB outcomes.

2.3. Primary and secondary outcomes

The co-primary outcomes were PA and/or SB, captured via objective measure (e.g. pedometers, accelerometers) or self-report validated tools (e.g. IPAQ (Craig et al., 2003)), in older adults (age ≥ 50 years old). Secondary outcomes of interest included physical (e.g. blood pressure, body mass, body mass index (BMI), body composition, lipid concentrations, glucose concentrations, cardiometabolic risk [e.g. measure of metabolic syndrome, composite scores of cardiometabolic risk markers], fall risk [e.g. had previous falls, walks with walking aid] and physical functioning [e.g. handgrip strength, RAND-36 physical functioning questionnaire, timed up and go]), mental health (such as depression), and social outcomes (such as reduced isolation, perceived loneliness) of PA and/or SB.

2.4. Data extraction

Data extracted by two reviewers (SS and research assistant) independently included: first author, year, country, region, setting, population, aims of the study, type of the study (controlled or randomized controlled trial, pre-post-test), number of participants, participant characteristics, details of the DBCI (including duration), inclusion criteria, type of recruitment, type and definition of SB or PA used, type of measurement of PA and SB, measurement of engagements/adherence to the DBCI, effects on PA and SB outcomes, specific BCTs used in DBCI (extracted by a trained coder (SS) using the Behavior Change Techniques Taxonomy v1 (BCTTv1) – 93 lower-order strategies which cluster into 16 groups of BCTs (Michie et al., 2013)), psychological or behavior change theoretical basis to the intervention (if mentioned), physical, mental and social outcomes analyzed in the results (if reported), details of control condition, confounding variables, acknowledged limitations by authors and authors conclusions, other/notes. Where information was missing, required clarification or particular variables of interest were not reported in the paper, corresponding authors were contacted to enable inclusion in the meta-analysis.

2.5. Quality assessment

Risk of bias was assessed by two independent researchers (SS and research assistant) using the Joanna Briggs Institute (JBI) critical appraisal checklist (Tufanaru et al., 2017). This tool was chosen as it provided flexibility and methodological appraisal for the study designs included in the review. For RCTs, the JBI checklist contained 13 items that were graded either ‘yes’, ‘no’, ‘unclear’ or ‘not applicable’ (see appendix B). The checklist for quasi-experimental studies contained nine items and was used for pre-post studies, containing nine ite ms that were graded either ‘yes’, ‘no’, ‘unclear’ or ‘not applicable’ (see appendix C). Discrepancies between the review authors were resolved by discussion, with involvement of a third review author (LS) where necessary. A greater number of ‘yes’ items indicated higher quality studies, thus lower risk of bias (Tufanaru et al., 2017).

2.6. Statistical analysis

The meta-analysis aimed to: i) establish the effects of DBCI on PA and SB on older adults, immediately at the end of the intervention and at follow-up, by extracting a pooled effect sizes (described below); ii) establish the effects of DBCI on physiological measures (e.g. weight, heart rate) by extracting a pooled effect size, iii) identify potential modifiers through meta-regression analysis, and iv) assess the influence of publication bias on reported effects.

Random effects meta-analyses calculating standardized mean difference (SMD), mean difference (MD) and 95% CI were conducted for RCT studies for total PA, number of steps per day, MVPA and total SB. For RCT studies meta-analyses investigating total PA and steps, studies were split by when measurement was taken – either immediately at the end of the intervention (EI) or at any later follow up (FU) – to allow differentiation between intervention and potential maintenance effects. Random effects meta-analysis calculating SMD, MD and 95% CI were conducted for pre-post studies for total PA and steps. For pre-post studies meta-analysis investigating total PA and steps, studies were split dichotomously by the number of BCT clusters used in the DBCI – ≥ 3 clusters or 1-2 clusters – as previous research suggests that a threshold of ≥ 3 clusters is required to see significant effects on PA (McEwan et al., 2018). Where possible, sources of heterogeneity and moderators were investigated with meta-regression analyses including; the number of BCTs used in the DBCI, type of PA measurement, age (years), sex (% males), year of publication, region (North America/non-North America), setting (community-based/ non-community-based) and intervention duration (weeks) were examined. Heterogeneity was assessed with the Cochrane Q and I^2 statistics for each analysis (Higgins et al., 2003). Values ≥ 50% indicated large heterogeneity and values ≥ 75% very large between studies heterogeneity (Higgins and Thompson, 2002; Ioannidis et al., 2007). Publication bias was assessed through a three-step process. First visual inspection of funnel plots for each analysis were assessed. Second, the Begg-Mazumdar Kendall's tau (Begg and Mazumdar, 1994) and Egger bias test (Egger et al., 1997) to quantify publication bias were calculated. Since a visual inspection of a funnel plot is somewhat subjective and interpretive, priority was given to quantitative testing of publication bias. Third, we conducted a trim and fill adjusted analysis to remove the most extreme small studies from the positive (or negative) side of the funnel plot, recomputing the effect size at each iteration, until the funnel plot is symmetric about the (new) effect size. All analyses were performed using Comprehensive meta-analysis (CMA, version 3) software (Biostat, New Jersey, USA).

3. Results

A total of 1990 records were originally identified from the database and four from grey literature searches. After removal of duplicates and title and abstract screening, 116 studies were selected for full-text review. Ninety-two articles were excluded on full-text review (see figure 1 for a breakdown of reasons for exclusion), leaving 22 articles included in the review. The PRISMA flow diagram of the study selection process can be seen in Figure 1.

Insert figure 1 here

Characteristics of the 22 included studies can be found in table 1. All studies were published between 2007 – 2017. Sample sizes ranged from 17 – 278 participants who completed the studies. Of the 22 studies, 14 were RCT study designs (participants with PA/SB data intervention n = 657, control n = 677) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; King et al., 2014; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012; Wijsman et al., 2013), five were pre-post study designs (n = 175) (Knight et al., 2015; Leutwyler et al., 2015; O'Brien et al., 2015; Strand et al., 2014; Tiedemann et al., 2015), one was a randomized crossover study design (n =12 intervention; n = 8 control) (Vidoni et al., 2016), one was a pre-test post-test quasi-experimental design (n = 24) (Williams, 2016), one was a mixed methods quasi-experimental two group pre-post study design (n = 13 intervention, n = 13 control) (Keogh et al., 2014). Study durations ranged from 6 – 52 weeks, with a median duration of 12 weeks. Most studies were from the North American region (N = 16), i.e. USA and Canada, two were from Oceania (Australia = 1; New Zealand = 1), one from Asia (Malaysia = 1) and only three were from Europe (Netherlands = 2; Belgium = 1).

Table 2 contains information regarding the DBCI, control treatment, BCTs and engagement/adherence in each study. Of all 22 studies, a psychological or behavior change theoretical basis to the intervention design was mentioned in only 11 studies; The Coventry, Aberdeen and London – Refined (CALO-RE) Taxonomy (Cadmus-Bertram et al., 2015; Lyons et al., 2017), social cognitive theory (Ashe et al., 2015; Cook et al., 2015; King et al., 2007; King et al., 2014; O'Brien et al., 2015), transtheoretical model (King et al., 2007; King et al., 2014; Strand et al., 2014), whole person wellness model (Strand et al., 2014), social-ecological model (Ashe et al., 2015), health promotion model (Williams, 2016), stages of change and I-Change model (Broekhuizen et al., 2016; Wijsman et al., 2013).

The most common BCTs were 1.1 goal setting (behavior) (n = 7) (Ashe et al., 2015; Broekhuizen et al., 2016; Kullgren et al., 2014; Lyons et al., 2017; Vidoni et al., 2016; Wijsman et al., 2013; Williams, 2016), 1.2 problem solving (n = 7) (Ashe et al., 2015; Bickmore et al., 2013; King et al., 2007; Lyons et al., 2017; Nguyen et al., 2009; O'Brien et al., 2015; Vidoni et al., 2016), 1.3 goal setting (outcome) (n = 5) (Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; King et al., 2007; Tiedemann et al., 2015; Wijsman et al., 2013), 2.2 feedback on behavior (n = 10) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Frederix et al., 2015; King et al., 2007; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Wijsman et al., 2013), 2.3 self-monitoring of behavior (n = 10) (Ashe et

al., 2015; Bickmore et al., 2013; Cadmus-Bertram et al., 2015; King et al., 2007; Knight et al., 2015; Lyons et al., 2017; Nguyen et al., 2009; O'Brien et al., 2015; Tiedemann et al., 2015; Vidoni et al., 2016), 3.1 social support (unspecified) (n = 16) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cook et al., 2015; Frederix et al., 2015; Keogh et al., 2014; King et al., 2007; Kullgren et al., 2014; Leutwyler et al., 2015; Lyons et al., 2017; Nguyen et al., 2009; Strand et al., 2014; Tiedemann et al., 2015; Vidoni et al., 2016; Wijsman et al., 2013; Williams, 2016), 4.1 instruction on how to perform a behavior (n = 15) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cook et al., 2015; Frederix et al., 2015; Keogh et al., 2014; Knight et al., 2015; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; O'Brien et al., 2015; Ruiz et al., 2012; Strand et al., 2014; Wijsman et al., 2013; Williams, 2016), 6.1 demonstration of the behavior (n = 7) (Ashe et al., 2015; Bickmore et al., 2013; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012; Strand et al., 2014; Williams, 2016), 7.1 prompts/cues (n = 4) (Ashe et al., 2015; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009), 8.1 behavioral practice/ rehearsal (n = 9) (Ashe et al., 2015; Bickmore et al., 2013; Frederix et al., 2015; Leutwyler et al., 2015; Müller et al., 2016; O'Brien et al., 2015; Ruiz et al., 2012; Strand et al., 2014; Williams, 2016), 9.1 credible source (n = 7) (Ashe et al., 2015; Broekhuizen et al., 2016; King et al., 2007; Lyons et al., 2017; Nguyen et al., 2009; Tiedemann et al., 2015; Wijsman et al., 2013) and 12.5 adding objects to the environment (n = 15) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; King et al., 2007; Leutwyler et al., 2015; Lyons et al., 2017; Nguyen et al., 2009; O'Brien et al., 2015; Ruiz et al., 2012; Strand et al., 2014; Tiedemann et al., 2015; Vidoni et al., 2016; Wijsman et al., 2013; Williams, 2016). The average number of BCTs reported in a study was 6.6 (range 2 – 23; median = 5.5) and the average number of BCT clusters was 5.10 (range 2 – 12; median = 5). Of the studies included in the present review, 91% used ≥3 BCT clusters within the DBCI and the remaining studies used 2 BCT clusters (Keogh et al., 2014; Knight et al., 2015).

3.1. Quality assessment

Of the 22 studies, 15 were evaluated using the RCT appraisal checklist (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; King et al., 2014; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012; Vidoni et al., 2016; Wijsman et al., 2013) and seven with the quasi-experimental (non-randomized) checklist (Keogh et al., 2014; Knight et al., 2015; Leutwyler et al., 2015; O'Brien et al., 2015; Strand et al., 2014; Tiedemann et al., 2015; Williams, 2016). Seven studies were deemed lower risk of bias (Keogh et al., 2014; Knight et al., 2015; Leutwyler et al., 2015; O'Brien et al., 2015; Strand et al., 2014; Tiedemann et al., 2015; Williams, 2016), 12 moderate risk of bias (Ashe et al., 2015; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; King et al., 2014; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Wijsman et al., 2013) and three higher risk of bias (Bickmore et al., 2013; Ruiz et al., 2012; Vidoni et al., 2016) (see appendix D).

In RCT studies, true randomization for assignment to groups was present in five studies (Ashe et al., 2015; Cook et al., 2015; Frederix et al., 2015; Kullgren et al., 2014) (see appendix D). Other studies were randomized but stratified by age (Cadmus-Bertram et al., 2015),sex (Broekhuizen et al., 2016; King et al., 2007; King et al., 2014; Nguyen et al., 2009; Wijsman et al., 2013), BMI (Cadmus-Bertram et al., 2015), clinic site and health literacy status (Bickmore et al., 2013) or enrolling with or without their spouse (Müller et al., 2016). Allocation to groups was concealed in eight studies (Ashe et al., 2015; Broekhuizen et al., 2016; Frederix et al., 2015; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Vidoni et al., 2016; Wijsman et al., 2013), was unclear in four studies (Cadmus-Bertram et al., 2015; King et al., 2007; King et al., 2014; Ruiz et al., 2012) and was not possible in three studies (Bickmore et al., 2013; Cook et al., 2015; Kullgren et al., 2014). Groups were similar at baseline in 11 studies (Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; King et al., 2014; Lyons et al., 2017; Müller et al., 2016; Ruiz et al., 2012; Wijsman et al., 2013), was unclear in one study (Nguyen et al., 2009), and were not similar in three studies due to weight at baseline (Ashe et al., 2015), number of steps walked at baseline (Kullgren et al., 2014), and cognitive impairment (with/without) and average weekly step count at baseline (Vidoni et al., 2016). A common feature was the inability to blind participants (n = 14) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; King et al., 2014; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012; Vidoni et al., 2016; Williams, 2016) and deliverers (n = 15) (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; King et al., 2014; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012; Vidoni et al., 2016; Williams, 2016) to group assignments due to the nature of the interventions. In addition, in seven of the RCT studies (Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; Ruiz et al., 2012; Vidoni et al., 2016; Wijsman et al., 2013) it was unclear whether the outcome assessors were blinded to group assignment and in two it was not possible (Lyons et al., 2017; Müller et al., 2016). Groups were treated identically in 12 studies (Ashe et al., 2015; Bickmore et al., 2013; Broekhuizen et al., 2016; Cadmus-Bertram et al., 2015; Cook et al., 2015; King et al., 2007; King et al., 2014; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Vidoni et al., 2016; Wijsman et al., 2013) and was unclear in two studies (Frederix et al., 2015; Ruiz et al., 2012). All 15 studies critically appraised using the RCT checklist adequately described and analyzed differences in groups at follow up, analyzed participants in the groups they were randomized, measured outcomes in the same way for all groups, outcomes were measured in a reliable way, used appropriate statistical analysis and the trial design was appropriate and accounted for any deviations.

Using the quasi-experimental (non-randomized) tool, all seven studies had clear cause and effect variable, participants in comparisons were similar and received similar treatment, multiple measures of outcomes were taken pre and post intervention, completed follow up and if not adequately described and analyzed differences, measured outcomes in the same and a reliable way, and appropriate statistical analysis was conducted (Keogh et al., 2014; Knight et al., 2015; Leutwyler et al., 2015; O'Brien et al., 2015; Strand et al., 2014; Tiedemann

et al., 2015; Williams, 2016) (see appendix D). Six studies did not have a control group; however, one study did have a control group (Keogh et al., 2014).

3.2. Main results

3.2.1. Physical Activity measurement

Outcome measures and confounding variables for each study can be found in table 3. All studies included in the review reported on PA outcomes. PA was measured objectively in 17 studies – four used Actigraph GT3X+ accelerometers (Ashe et al., 2015; Cadmus-Bertram et al., 2015; Ruiz et al., 2012; Tiedemann et al., 2015), two used Omron pedometers (Bickmore et al., 2013; Knight et al., 2015), two used GeneActiv accelerometers (Broekhuizen et al., 2016; Wijsman et al., 2013), one used an ActivPAL inclinometer (Lyons et al., 2017), one used Yorbody accelerometer (Frederix et al., 2015), three used a Fitbit (Kullgren et al., 2014; Tiedemann et al., 2015; Vidoni et al., 2016), one used a Nike Fuel wristband (O'Brien et al., 2015), one used a SenseWear Pro Armband (Leutwyler et al., 2015), one used a Stepwatch 3 (Nguyen et al., 2009) – and using self-report questionnaires in seven studies – one used the Godin Leisure-Time Exercise Questionnaire (Cook et al., 2015), one used the International Physical Activity Questionnaire (IPAQ) (Müller et al., 2016), two used the Rapid Assessment of Physical Activity questionnaire (RAPA) (Keogh et al., 2014; Williams, 2016), two used the Stanford 7-day physical activity recall (PAR) (King et al., 2007; King et al., 2014), one used the Cancer Prevention Research Centers Stages of Change Physical Activity (Strand et al., 2014) (see table 3).

3.2.2.1. Total physical activity narrative results

Overall 15 studies, including 10 RCTs (Ashe et al., 2015; Bickmore et al., 2013; Cadmus-Bertram et al., 2015; Frederix et al., 2015; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012; Vidoni et al., 2016) and five pre-post-test studies (Keogh et al., 2014; Knight et al., 2015; O'Brien et al., 2015; Tiedemann et al., 2015; Williams, 2016) measured total PA. Objectively measured steps were used in the total PA meta-analysis where available (Ashe et al., 2015; Bickmore et al., 2013; Cadmus-Bertram et al., 2015; Knight et al., 2015; Kullgren et al., 2014; Lyons et al., 2017; Nguyen et al., 2009; O'Brien et al., 2015; Tiedemann et al., 2015; Vidoni et al., 2016), and questionnaire data on PA was also used (Keogh et al., 2014; Müller et al., 2016; Ruiz et al., 2012; Williams, 2016). PA measured by step count was reported as median and interquartile range in Frederix et al. (2015) so was not entered into the meta-analysis model. PA in Strand et al. (2014) was reported as the number of people who has a change in self-reported PA – by week 8 five inactive people became active and by week 25 6 more became active – so was not entered into the meta-analysis model. No score of total PA was available or calculable for Broekhuizen et al. (2016), King et al. (2007), King et al. (2014), Leutwyler et al. (2015) or Wijsman et al. (2013).

3.2.2.2. Total physical activity meta-analysis results

For the meta-analysis on total PA, Vidoni et al. (2016) was entered as a pre-post study rather than an RCT using only participants without cognitive impairment for more appropriate comparisons between studies. Among RCT (EI), DBCI significantly increased total PA (N = 8, n = 450, SMD = 0.28; 95% CI 0.01, 0.56; p = 0.04; I^2 = 47%) (table 4)(Ashe et al., 2015; Bickmore et al., 2013; Cadmus-Bertram et al., 2015; Kullgren et al., 2014; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Ruiz et al., 2012). A pooled analysis of two RCT (FU) studies (Bickmore et al., 2013; Kullgren et al., 2014) showed no increase in total PA (n = 255, SMD = 0.11; 95% CI -0.14, 0.36; p = 0.39; I^2 = 0%). Between-groups difference in total PA was found between RCT (EI) and RCT (FU) study designs (SMD = 0.19; 95% CI 0.004, 0.37; p = 0.05). DBCI significantly increased total PA in pre-post studies (N = 6, n = 159, SMD = 0.25; 95% CI 0.09, 0.41; p = 0.002; I^2 = 37%) (Keogh et al., 2014; Knight et al., 2015; O'Brien et al., 2015; Tiedemann et al., 2015; Vidoni et al., 2016; Williams, 2016).

Among RCT (EI) with objectively measured PA, DBCI had no effect on total PA (N = 7, n = 411, SMD = 0.28; 95% CI -0.02, 0.06; p = 0.07; I2 = 52%) (Ashe et al., 2015; Bickmore et al., 2013; Cadmus-Bertram et al., 2015; Kullgren et al., 2014; Lyons et al., 2017; Nguyen et al., 2009; Ruiz et al., 2012). One RCT (EI) study subjectively measured total PA and found no increase in total PA (SMD = 0.36, 95%CI -0.27, 1.00, p = 0.27; I^2 = 0%) (Müller et al., 2016). A between-groups difference in total PA was found between objectively and subjectively measured PA in RCT (EI) (SMD = 0.30; 95% CI 0.02, 0.57; p = 0.03). Two RCT (FU) studies objectively measured total PA, thus results were the same as above and not reported again. DBCI significantly increased total PA in pre-post studies with objectively measured PA (N = 4, n = 122, SMD = 0.24; 95% CI 0.02, 0.45; p = 0.03; I^2 = 51%) (Knight et al., 2015; O'Brien et al., 2015; Tiedemann et al., 2015; Vidoni et al., 2016). Among subjectively measured PA pre-post studies, DBCI significantly increased total PA (N = 2, n = 37, SMD = 0.27; 95% CI 0.02, 0.53; p = 0.04; I^2 = 0%) (Keogh et al., 2014; Williams, 2016). Between-groups difference in total PA was found between pre-post studies measuring PA objectively and subjectively (SMD = 0.25; 95% CI 0.09, 0.41; p = 0.003).

Among pre-post studies, DBCI with ≥3 BCT clusters significantly increased total PA (N = 4, n = 101, SMD = 0.37; 95% CI 0.21, 0.53; p < 0.001; I^2 = 0%) (table 4) (O'Brien et al., 2015; Tiedemann et al., 2015; Vidoni et al., 2016; Williams, 2016). In pre-post studies, DBCI with 1-2 BCT clusters had no effect on total PA (N = 2, n = 21, SMD = 0.09; 95% CI -0.14, 0.32; p = 0.44; I^2 = 21.93%) (Keogh et al., 2014; Knight et al., 2015). Between-groups difference in total PA was found between DBCI with 1-2 BCT clusters and ≥3 BCT clusters (SMD = 0.28; 95% CI 0.15, 0.24; p < 0.001; I^2 = 36.60%). Meta-analysis on total PA grouped by BCT cluster was not possible for RCT studies as all DBCI included ≥3 clusters.

3.2.3.1. Steps (per day) narrative results

Steps per day were available for 11 studies (RCT = 8, pre-post = 3). Frederix et al. (2015) reported a pre-intervention daily step count (median = 7748, IRQ = 24) and post intervention at 6 weeks this had increased (median = 7799, IQR 37) and at 24 weeks had further increased

(median = 8233, IQR = 32), however these changes were not significant (p = 0.24). As steps were reported as medians, likely due to the means being skewed, they were unable to be included in the meta-analysis. One study reported the number of participants that had no change in steps per day (n = 5) and who significantly increased their steps per day (n = 10) (Leutwyler et al., 2015). In Vidoni et al. (2016), for participants without cognitive impairment, weekly step count increased by 15530 steps (SD = 18950, p = 0.05); however weekly increase was reported – rather than daily – it was deemed inappropriate to assume a 7 day week and estimate standard deviations for daily steps. Therefore, this study was not included in the meta-analysis. Steps were not reported in seven studies (Broekhuizen et al., 2016; Cook et al., 2015; King et al., 2007; King et al., 2014; Strand et al., 2014; Wijsman et al., 2013; Williams, 2016).

3.2.3.2. Steps (per day) meta-analysis results

Among RCT (EI), DBCI showed no significant effect on steps per day (N = 6, n = 383, SMD = 0.18; 95% CI -0.03, 0.38; p = 0.09; I^2 = 0%; MD = 401; 95% CI -125, 926; p = 0.13) (table 4) (Ashe et al., 2015; Bickmore et al., 2013; Cadmus-Bertram et al., 2015; Kullgren et al., 2014; Lyons et al., 2017; Nguyen et al., 2009). DBCI also showed no significant effect on daily step count in RCT (FU) studies (N = 2, n = 255, SMD = 0.11; 95% CI -0.14, 0.36; p = 0.39; I^2 = 0%; MD = 280 steps; 95% CI -508, 1068; p = 0.49) (Bickmore et al., 2013; Kullgren et al., 2014). No between-groups difference in steps was found between RCT (EI) and RCT (FU) (p = 0.06). Among pre-post studies, DBCI significantly decreased daily step count (N = 3, n = 122, SMD = -0.20; 95% CI -0.42, 0.02; p = 0.08; I^2 = 54%; MD = -737 steps; 95% CI -1361, -113; p = 0.02) (Knight et al., 2015; O'Brien et al., 2015; Tiedemann et al., 2015).

Among pre-post studies, DBCI with ≥3 BCT clusters showed a significant decrease in steps per day (N = 2, n = 77, SMD = -0.41; 95% CI -0.60, -0.22; p <0.001; I^2 = 0%) (table 4) (O'Brien et al., 2015; Tiedemann et al., 2015; Vidoni et al., 2016). In pre-post studies, DBCI with 1-2 BCT clusters had no significant effect on steps per day (N = 1, n = 45, SMD = 0.12; 95% CI -0.22, 0.24; p = 0.95; I^2 = 0%) (Knight et al., 2015). Between-groups difference in steps per day was found between DBCI 1-2 BCT clusters and ≥3 BCT clusters (SMD = -0.24; 95% CI -0.38, -0.09; p = 0.002; I^2 = 53.55%. Meta-analysis on steps per day grouped by BCT cluster was not possible for RCT studies as all DBCI included ≥3 clusters.

3.2.4.1. MVPA (min/week) narrative results

In total, 10 studies measured MVPA, of which eight were RCTs (Ashe et al., 2015; Cadmus-Bertram et al., 2015; Cook et al., 2015; Frederix et al., 2015; King et al., 2007; Lyons et al., 2017; Nguyen et al., 2009; Wijsman et al., 2013) and two were pre-post studies (King et al., 2014; Leutwyler et al., 2015). MVPA was measured objectively in minutes per day in five studies (Ashe et al., 2015; King et al., 2007; King et al., 2014; Lyons et al., 2017; Wijsman et al., 2013), minutes per week in one study (Cadmus-Bertram et al., 2015). MVPA was measured using questionnaires in two studies; one converted to MET-min/week (Frederix et

al., 2015) and the other as a percentage time at moderate-high PA (Nguyen et al., 2009). In Cook et al. (2015), MVPA was measured by Godin questionnaire however reported a change in strenuous, moderate and mild exercise separately, compared to the control. Back calculations were not possible therefore it was deemed inappropriate to combine these and enter them into a meta-analysis. In Leutwyler et al. (2015) only the numbers of participants who demonstrated increases in moderate hours of PA (n =7) and those who did not (n = 8) were reported, no comparable measure of MVPA was reported so was not included in the meta-analysis model.

3.2.4.2. MVPA (min/week) meta-analysis results

Among RCTs, DBCI significantly increased MVPA (N = 6, n = 694, SMD = 0.47; 95% CI 0.32, 0.62; $p < 0.001$; $I^2 = 0\%$; MD [N=3] = 51.97; 95% CI 23.91, 80.03; $p < 0.001$) (Ashe et al., 2015; Cadmus-Bertram et al., 2015; Frederix et al., 2015; King et al., 2007; Nguyen et al., 2009; Wijsman et al., 2013). Significant increases in MVPA were shown among RCT (EI) that objectively measured PA (N = 5, n = 443, SMD = 0.53; 95% CI 0.34, 0.72; $p < 0.001$; $I^2 = 0\%$; MD = 10.14; 95% CI -2.33, 22.61; p = 0.11). RCT (EI) that subjectively measured PA also showed increases in MVPA (N = 1, n = 251, SMD = 0.38; 95% CI 0.13, 0.63; $p < 0.001$; $I^2 = 0\%$; MD = 49.71; 95% CI 17.17, 82.26; p = 0.003). Between-groups difference in MVPA was found between objectively and subjectively measured RCT (EI) studies (SMD = 15.20; 95% CI 3.56, 26.84; $p < 0.001$). Due to an insufficient number of studies available, meta-analysis on MVPA was not possible for pre-post studies.

3.2.5.1 Sedentary behavior (min/day) narrative results

In total 7 studies measured SB which was measured objectively in five studies – one used Actigraph GT3X+ (Ashe et al., 2015), one used ActivPAL (Lyons et al., 2017), one used SenseWear Pro Armband (Leutwyler et al., 2015), one used a Stepwatch 3 (Nguyen et al., 2009) – and two using the IPAQ self-report questionnaire (Frederix et al., 2015; Müller et al., 2016). Sedentary minutes per day were reported in three studies (Ashe et al., 2015; Lyons et al., 2017; Müller et al., 2016), minutes per week in one study (Frederix et al., 2015), sedentary time as a percentage of the day in one study (Nguyen et al., 2009) and the number of participants that changed sedentary time (increase/decrease) in one study (Leutwyler et al., 2015).

3.2.5.2. Sedentary behavior (min/day) meta-analysis results

Across RCTs, DBCI significantly reduced SB (N = 5, n = 255, SMD = -0.44; 95% CI -0.69, -0.19; $p < 0.001$; $I^2 = 0\%$; MD [N = 3] = 58.49; 95% CI -100.34, -16.64; $p < 0.001$) (table 4) (Ashe et al., 2015; Frederix et al., 2015; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009). Among RCT (EI) studies that measured SB objectively, DBCI significantly reduced SB (N = 4, n = 216, SMD = -0.45; 95% CI -0.72, -0.17; p = 0.001; $I^2 = 0\%$; MD = -33.47; 95% CI -90.63,

23.70; p = 0.25) (Ashe et al., 2015; Frederix et al., 2015; Lyons et al., 2017; Nguyen et al., 2009). No significant change in SB was found in RCT (EI) that measured SB subjectively (N = 1, n = 39, SMD = -0.40; 95% CI -1.04, 0.23; p = 0.22; I^2 = 0%; MD = -0.76, 95% CI -1.95, 0.43; p = 0.21) (Müller et al., 2016). Between-groups difference was found between objectively and subjectively measured SB in RCT (EI) (SMD = -0.44; 95% CI -0.69, -0.19; p < 0.001). Due to an insufficient number of studies available, meta-analysis on SB was not possible for pre-post studies.

3.2.6 Secondary outcomes

Common secondary outcomes that were measured in at least five or more papers have been reported on separately, including weight, blood pressure, physical functioning and quality of life. For all secondary outcomes of each study see table 3. Due to the number of studies available measuring the respective comparators, meta-analysis was only possible for RCT studies.

3.2.6.1. Weight meta-analysis

Seven studies measured the impact of DBCI on body weight; five RCTs (Ashe et al., 2015; Cadmus-Bertram et al., 2015; Frederix et al., 2015; Lyons et al., 2017; Wijsman et al., 2013) and two pre-post studies (Broekhuizen et al., 2016; Knight et al., 2015). Among RCTs, DBCI had no significant effect on weight (N = 5, n = 466, SMD = -0.15; 95% CI -0.33, 0.03; p = 0.10; I^2 = 0%; MD = -0.68kg; -3.45, 2.09; p = 0.63) (table 5).

3.2.6.2. Blood Pressure meta-analysis

Five studies measured the impact of DBCI on blood pressure; three RCTs (Ashe et al., 2015; Frederix et al., 2015; Wijsman et al., 2013) and two pre-post studies (Knight et al., 2015; O'Brien et al., 2015). It is important to note that Wijsman et al. (2013) was automatically removed from the model when analyzing mean differences due to blood pressure being measured as a change in, resulting in only 81 in the intervention and 78 in the control mean difference analysis. DBCI significantly decreased systolic blood pressure (SBP) among RCTs (N = 3, n = 375, SMD = -0.14; 95% CI -0.35, 0.07; p = 0.18; I^2 = 4%; MD = -11bpm; 95% CI -21.96, -0.71, p = 0.04) (table 5). DBCI showed no significant effect on diastolic blood pressure (DBP) (SMD = 0.10; 95% CI -0.30, 0.09; p = 0.30; I^2 = 0%; MD = -3bpm; 95% CI -9.00, 2.93; p = 0.32).

3.2.6.3. Physical Functioning meta-analysis

Nine studies measured physical functioning; seven RCT (Broekhuizen et al., 2016; Frederix et al., 2015; Lyons et al., 2017; Müller et al., 2016; Nguyen et al., 2009; Vidoni et al., 2016; Wijsman et al., 2013) and two pre-post studies (Keogh et al., 2014; O'Brien et al., 2015). Similar to total PA, Vidoni et al. (2016) was considered a pre-post study rather than an RCT

using only participants without cognitive impairment for more appropriate comparisons between studies. Broekhuizen et al. (2016) and Wijsman et al. (2013) reported different measures of physical functioning of the same intervention with the same participants. It was deemed inappropriate to include both in a meta-analysis, and as Wijsman et al. (2013) reported outcomes that were able to be used in other meta-analyses, it was decided that for continuity that physical functioning data from Wijsman et al. (2013) only would be included. Many different methods were used to measure physical functioning across studies; using the physical functioning score from the RAND-36 questionnaire (Broekhuizen et al., 2016), VO2 peak (Frederix et al., 2015), bicep curls in 30 seconds through full range of motion (Keogh et al., 2014), 6-minute walking test (Lyons et al., 2017; Nguyen et al., 2009; Vidoni et al., 2016), timed up and go (TUG) (O'Brien et al., 2015) and grip strength (Müller et al., 2016; Wijsman et al., 2013). Among RCTs, DBCI significantly improved physical functioning in older adults (N = 5, n = 451, SMD = 0.21; 95% CI 0.03, 0.40; p = 0.03; I^2 = 0%) (table 5).

3.2.6.4. Quality of Life meta-analysis

Five studies measured the impact of DBCI on QoL; three RCTs (Broekhuizen et al., 2016; Frederix et al., 2015; Nguyen et al., 2009) and two pre-post studies (Keogh et al., 2014; Vidoni et al., 2016). Among RCT studies, DBCI had no significant effect on QoL scores in older adults (N = 3, n = 372, SMD = 0.27; 95% CI -0.2, 0.57; p = 0.07; I2 = 37.92%) (table 5).

3.3. Meta-regression

Meta-regression analysis was only possible for total PA RCT (EI) studies as other meta-analyses presented above contained too few studies (n < 10). Independently, the number of BCTs used in an intervention, the type of PA measurement (objective/subjective), the mean age of participants, the percentage of males, the publication year, the region (North America/ non-North America), the setting of the intervention (i.e. community based / non-community based), or the duration (weeks) of the intervention did not impact total PA (p > 0.05). The variance between studies could be partially accounted for in the number of BCTs used (r^2 = 0.24), mean age of participants (r^2 = 0.06) and the year of publication (r^2 = 0.07), accounting for approximately 37% of the variance seen between studies (table 6).

4. Discussion

To the best of our knowledge, this is the first systematic review and meta-analysis to assess the effects of using DBCI to target PA and/or SB in older adults (≥ 50 years old). The current meta-analyses suggest that among RCT (EI) studies, DBCI increased total PA (SMD = 0.28, p = 0.04), increased MVPA (SMD = 0.47, p < 0.001; MD = 52, p < 0.001) and reduced sedentary time (SMD = -0.44, p < 0.001; MD = -58, p <0.001) when compared with control conditions. Similar increases in total PA were also shown in pre-post studies (SMD = 0.25, p = 0.002). Reductions in systolic blood pressure and improvements in physical functioning were identified among RCTs.

DBCI increased total PA in both RCT and pre-post study designs when measured immediately at the end of the intervention, however from the two follow-up RCT studies it appears this was not maintained long-term. Similarly, in a systematic review of reviews, Zubala et al. (2017) found non-digital PA interventions often resulted in increases in PA in older adults (≥ 50 years), but effective maintenance beyond one year was unclear. It appears that DBCI have the potential to increase total PA in older adults, but may face similar problems to traditional methods regarding maintenance, although this is still unknown. Between-groups differences were seen between objectively and subjectively measured total PA in both RCT (End Intervention) and pre-post studies, however, these results must be interpreted with caution due to very low numbers of studies in subgroups. Self-reported PA often overestimates actual PA levels (Colbert et al., 2011; Prince et al., 2008) and this was evident in the meta-analysis, with the subjectively measured study reporting a larger increase in total PA than objectively measured.

Increases in MVPA were shown in the present meta-analysis, equivalent to 52 min/week. This is important as it represents 35% of the 150 min/week recommendation for older adults (Public Health England, 2014). Similar increases were shown in a meta-analysis conducted by Roberts et al. (2017), who found MVPA increased by approximately 40 min/week in cancer survivors when they engaged with a DBCI to promote PA. Additionally, a multilevel PA intervention in older adults (≥ 65 years), including group walks, individual counselling and self-monitoring with pedometers, increased MVPA by 56 minutes per week (Kerr et al., 2018). The present study found between-groups differences in MVPA in RCT (End Intervention) studies when measured objectively vs. subjectively; however, it must be noted that only one study measured MVPA subjectively thus statistical significance should be interpreted with caution. Similarly, a previous random effects meta-analysis of RCT studies using wearable and smartphone apps in adults (≥ 18 years) showed improvements in objectively measured MVPA but not in subjectively measured MVPA (Gal et al., 2018). This suggests that objective PA measurement is required to accurately assess the efficacy of such interventions.

No effect was found on daily step count in either RCT or pre-post designs, although non-significant, greater increases were shown in the short term and attenuated at follow up. Unexpectedly, a reduction in the number of steps taken per day equivalent to 737 steps per day was found in the MD of pre-post studies, despite indications of increases in total PA and MVPA. An explanation for this could be due to low numbers of studies and participants in the

calculations, or that total PA and MVPA increased due to non-ambulatory activities such as cycling or swimming. Conversely, a previous meta-analysis of non-digital PA interventions in older adults (≥ 65 years) showed an increase of 620 more steps/day in the intervention group compared with the control group (Chase, 2015). Previous random-effects meta-analysis of RCT studies showed that smartphone apps and wearable interventions significantly increased daily step counts in adults (≥ 18 years) (Gal et al., 2018). DBCI may have potential to increase daily step counts in older adults, particularly in the short term, but more research is required.

The present meta-analyses showed DBCIs were associated with a significant reduction in SB, equivalent to 58 min/day. Similarly, a goal-setting-based non-digital intervention to reduce SB in older adults (≥ 60 years) showed significant reductions in total sitting time of 51.5 minutes per day (Lewis et al., 2016). Reduction in SB was seen in the present study when SB was measured objectively but not subjectively, although only one study measured SB subjectively so effect sizes must be interpreted with caution. Subjective measurement has previously been shown to significantly underestimate SB in older adults (Copeland et al., 2017; Van Cauwenberg et al., 2014), therefore future studies should aim to measure SB objectively when possible.

One of the most common BCTs in the present review was social support, and evidence suggests older adults are more likely to engage in PA if meaningful motivators such as social and environmental support and enjoyment are present, rather than purely cognitive strategies or BCTs (Zubala et al., 2017). In the present review, goal setting and feedback on behavior were also commonly present. Similarly, goal setting, feedback and self-monitoring behaviors were common in DBCI in cancer survivors (Roberts et al., 2017) and in eHealth interventions – using information and communication technologies for health – in older adults (≥ 55 years) (Muellmann et al., 2017). These BCTs were common among apps and wearables showing the most significant improvements in behavioral and health outcomes (Schoeppe et al., 2016). Therefore, the BCTs goal setting, feedback, self-monitoring and social support should be considered when designing future DBCI for older adults.

A recent meta-analysis of 224 PA interventions found no linear associations between PA and the number of BCT clusters; however, the authors suggest a minimum of three BCT clusters are needed to produce significant effects on PA (McEwan et al., 2018). The present meta-analyses in pre-post studies supports previous findings of a ≥3 BCT cluster threshold for significant effects on total PA and steps per day to be found. In addition, all RCT studies used DBCI with ≥3 BCT clusters and had significant effects on total PA, MVPA and also SB. Future DBCI should therefore consider utilizing BCTs from three or more different clusters in order to significantly effect changes in behavior.

Secondary outcome meta-analysis showed no change in weight, DBP or QoL. Explanations for this could be due to the limited number of studies measuring these outcomes, the DBCI were too short-term to influence these factors, or extraneous factors (such as diet or mental health) impacted these outcomes. Nevertheless, engaging in DBCI reduced SBP by approximately 11bpm, but did not affect DBP. Similarly, a multilevel non-digital PA program in older adults (≥ 65 years) showed significant reductions in SBP (6.8 bpm; SD = 3.2) and DBP (2.5 bpm; SD = 1.9) at 6 months into the intervention (Kerr et al., 2018). Increases in PA may

induce post-exercise hypotension (MacDonald, 2002), thus may be important for helping to manage blood pressure in older adults. Physical functioning was significantly increased by DBCI in the present meta-analysis, which may be due to improvements in stamina, strength, balance, coordination or increased movement confidence associated with increased PA, and have been documented previously in older adults engaging in exergames (De Queiroz et al., 2017; Howes et al., 2017; Molina et al., 2014; Pope et al., 2017; Skjaeret et al., 2016), web-based (Irvine et al., 2013) and non-digital PA and exercise programs (Barnett et al., 2003; Chodzko-Zajko et al., 2009; Taylor et al., 2004). This suggests that DBCI designed to increase PA and/or reduce SB can also improve physical functioning, even if this is not the targeted outcome.

DBCI have the potential to increase PA and physical functioning, and reduce SB and SBP in older adults. This can lead to the prevention and/or maintenance of NCD and greater independence associated with healthy ageing (Chad et al., 2005; Daskalopoulou et al., 2017; Smith et al., 2015; Tak et al., 2013). As future populations comprise greater proportions of older adults and life expectancies continue to increase, it is important that health, QoL and years lived without disability are maximized, for the individual and for society.

4.1. Strengths and limitations

Strengths of this review include that it is the first systematic review and meta-analysis to assess the effectiveness of DBCI on PA and/or SB in older adults aged ≥ 50 years, and was conducted and reported in line with PRISMA guidelines (Moher et al., 2009). The inclusion of studies using exclusively older adults aged ≥ 50 years ensured our findings were completely relevant to this specific population. Lastly this review has highlighted the lack of UK studies investigating DBCI for PA and SB in older adults. One limitation of this review is the relative infancy of the topic area meaning many studies are feasibility focused with small sample sizes, which may impact efficacy estimates. Many studies in this review were short-term interventions with no follow-up, thus we cannot be sure of the long-term effects of DBCI on PA and SB in older adults. In addition, some meta-analyses reported moderate to high heterogeneity and potential publication bias, although potentially due to variability in the type of DBCI and specific intervention content (Roberts et al., 2017), should be interpreted with caution. It was not possible to compare DBCI to a wait-list/no intervention control vs. a non-digital intervention due to the lack of studies, which may statistically impact effect sizes. In addition, BCTs for control conditions were not coded, but may elicit behavior change or show overlaps with the DBCI, potentially influencing effect sizes. Due to insufficient quantity of studies, it was not possible to conduct meta-regression analysis on most outcomes. Only studies reported in English were reviewed, meaning eligible studies in other languages may have been missed. The terms ‘web-based’, ‘internet’ and ‘pedometer’ were actively excluded from the search methodology, as in pilot searches this elicited unmanageable volumes of results, however may mean some eligible papers may have been missed. The grey literature search should have helped minimize this.

Future research should continue to investigate the efficacy of DBCI compared with non-digital conditions as well as wait-list/no intervention control conditions, and investigate longer-term interventions with follow-ups to investigate the maintenance of PA post-intervention. More information regarding which BCTs make a DBCI more or less effective in promoting PA and/or reducing SB in older adults is also needed. Thus, authors are encouraged to explicitly list the BCTs used in their DBCI, for the intervention and control groups, which may show overlap in BCTs between the groups potentially affecting the magnitude of effects shown. This could also lead to a more comprehensive meta-analysis of studies in the future. Investigators should continue to use objective measures of PA and SB where possible. Older adults ownership of digital devices is increasing; in the USA, 74% of older adults aged 50-64 years old and 42% aged ≥ 65 years old own a smart phone (Pew Research Centre, 2017); similarly in the UK 51% of older adults aged ≥55 years old have a smartphone and 48% have a tablet device (Ofcom, 2018). A survey conducted in the USA found that of smartphone users aged ≥ 50, 26% have software on their phones to track or manage their health, which is comparable to those aged 18 – 29 years old at 24% (Fox and Duggan, 2012). Therefore, mobile/tablet apps as a method for delivering DBCI to older adults should be explored further.

4.2. Conclusion

In conclusion, there is evidence that DBCI to promote PA and/or reduce SB result in increases in total PA, MVPA and physical functioning, and reductions in SB and SBP in older adults aged ≥ 50 years, at least in the short term. Further research is required to investigate medium- and long-term interventions, maintenance effects and DBCI compared with no intervention and non-digital interventions control groups. Differences between objective and subjectively measured PA and SB were shown, thus future researchers should aim to objectively measure these where possible. DBCI used with older adults commonly feature the BCTs social support, goal setting and feedback, however future research is needed to identify specifically the effectiveness of each BCT, which will also enhance DBCI design. Researchers should also consider coding BCTs from control groups as there may be overlaps with the DBCI, which could influence effect sizes.

5. Tables and Figures

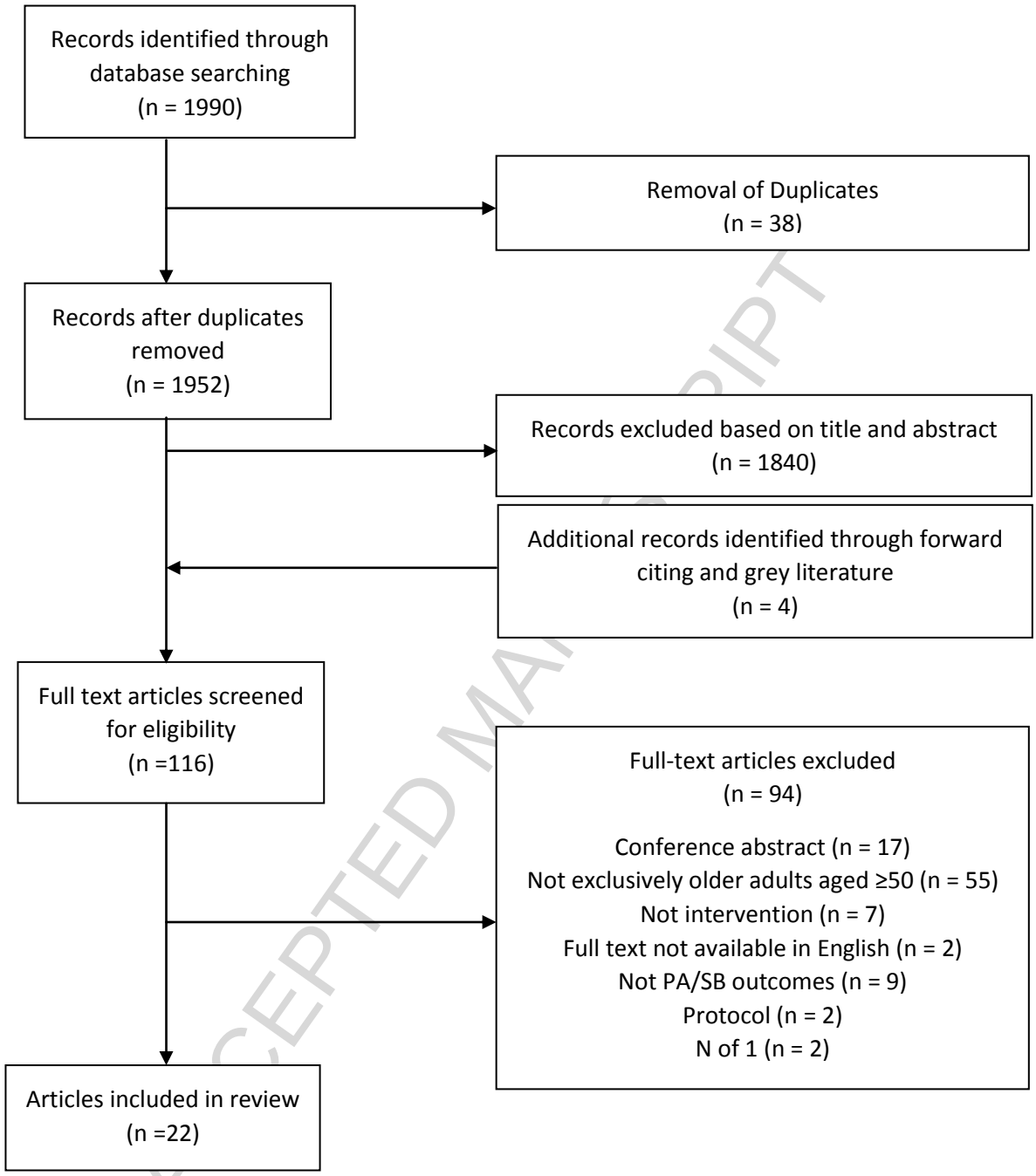

Figure 1. PRISMA flow diagram illustrating article selection strategy

Table 1. Characteristics of included studies

Author, year	Country	Study design	Sample size	Retention rate at follow-up	Men %	Age in years mean (SD)	Age range (yrs)	Physical activity measurement	Sedentary behavior measurement
Ashe, 2015	Canada	RCT	20 Int. = 12 Con. = 8	80% (20/25)	0	64.95 (4.7)	55-70	Accelerometer (Actigraph GT3X+)	Accelerometer (Actigraph GT3X+)
Bickmore, 2013	USA	RCT	113 Int. = 55 Con. = 58	48.7% (128/263)	38.8	71.3 (5.4)	65+	Accelerometer (Omron pedometer HJ-720ITC)	n/a
Broekhuizen, 2016	Netherlands	RCT	216 Int. = 107 Cont. = 109	95.7% (225/235)	59.1	64.8 (2.9)	60-70	Accelerometer (GeneActiv – wrist worn)	n/a
Cadmus-Bertram, 2015	USA	RCT	51 Int. = 25 Con. = 26	100% (51/51)	0	60 (7.1)	Not provided	Accelerometer (Actigraph GT3X+)	n/a
Cook, 2015	USA	RCT	278 Int. = 138 Con. = 140	100% (278/278)	67.3	Not provided	50-68	Godin Leisure-time exercise questionnaire	n/a
Frederix, 2015	Belgium	RCT	139 Int. = 69 Con. = 70	99.3% (139/140)	81.4	61 (8.5)	Not provided	Accelerometer (Yorbody)	IPAQ
Keogh, 2014	New Zealand	Pre – post mixed methods	26 Int. = 13 Con. = 13	100% (34/34)	11.8	83 (8)	Not provided	Rapid Assessment of Physical Activity questionnaire (RAPA)	n/a
King, 2007	Canada	RCT	189 Automate	78.3% (148/189)	Not Provi	60 (5.5)	55+	Stanford 7-day physical activity	n/a

			d = 61 Human = 66 Con. = 62		ded			recall (PAR)	
King, 2014	Canada	RCT	127 Automated = 61 Human = 66	86.7% (189/218)	30.7	60 (5.5)	55+	Stanford 7-day physical activity recall (PAR)	n/a
Knight, 2015	Canada	Pre – post	45 Exercise = 15 Sedentary = 14 Counselling = 16	100% (45/45)	44.4	63 (5)	55-75	Accelerometer (Omron pedometer HJ-150)	n/a
Kullgren, 2014	Canada	RCT	92 Financial = 20 Peer = 22 Combined = 25 Con. = 25	92.4% (85/92)	30	71.9 (5.6)	65+	Accelerometer (Fitbit)	n/a
Leutwyler, 2015	Canada	Pre – post	15	100% (20/20)	80	60.3 (4.4)	55+	Accelerometer (SenseWear Pro Armband)	Accelerometer (SenseWear Pro Armband)
Lyons, 2017	USA	RCT	40 Int. = 20 Con. = 20	100% (40/40)	15	61.5 (5.6)	55-79	Accelerometer (ActivPAL)	Accelerometer (ActivPAL)

Müller, 2016	Malaysia	RCT	39 Int. 18 Con. = 21	90.7% (39/43)	26	63.3 (4.5)	55-70	IPAQ	IPAQ
Nguyen, 2009	USA	RCT	17 Int. = 9 Con. = 8	94.4% (17/18)	35.3	68 (10.5)	52-81	Accelerometer (Stepwatch 3 Activity Monitor)	Accelerometer (Stepwatch 3 Activity Monitor)
O'Brien, 2015	Canada	Pre – post	34	100% (34/34)	35	73.5 (9.4)	60-96	Accelerometer (Nike Fuel wristband)	n/a
Ruiz, 2012	Canada	RCT	21 Self = 7 Other = 7 Con. = 7	93.3% (28/30)	96.4	62 (6)	50+	Accelerometer (Actigraph GT3X)	n/a
Strand, 2014	Canada	Pre – post	46	67.6% (46/68)	13	Not provided	60+	Cancer Prevention Research Centers Stages of Change Physical Activity	n/a
Tiedemann, 2015	Australia	Pre – post	35	92.1% (35/38)	34	67.7 (5.5)	60+	Accelerometer (Pre-Actigraph; Post-Fitbit)	n/a
Vidoni, 2016	Canada	Randomized cross over	20 Cog Imp = 12 Con. = 8	69% (20/29)	69	71 (5.5)	60-85	Accelerometer (Fitbit Zip)	n/a
Wijsman, 2013	Netherlands	RCT	216 Int. = 107 Con. = 109	96.2% (226/235)	59.1	64.8 (2.9)	60-70	Accelerometer (Geneactiv ankle and wrist worn)	n/a
Williams, 2016	Canada	Pre – post quasi-	24	100% (24/24)	33.3	79.33 (11.09)	50-99	RAPA Questionnaire	n/a

experimental

Int., Intervention; Con., Control

Table 2 Intervention types from included studies

Author, year	Intervention type	Study duration (weeks)	Description of intervention	Control group treatment	Behavior change techniques (BCTs)*	Approaches to measurement of engagement/ adherence
Ashe, 2015	Fitbit One	24	Group-based education and social support, individualized PA prescription, use of activity monitor (Fitbit One). Phase 1 'ramp up' 4 weekly sessions. Phase 2 'activation' 5 monthly sessions.	Monthly education sessions similar to intervention group. No Fitbit, no information on importance of exercise, no interactions with exercise professionals.	1.1 Goal setting (behavior), 1.2 Problem solving, 1.4 Action planning, 2.2 Feedback on behavior, 2.3 Self-monitoring of behavior, 3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 5.3 Information about social and environmental consequences, 6.1 Demonstration of the behavior, 6.2 Social comparison, 7.1 Prompts/cues, 8.1 Behavioral practice/rehearsal, 8.2 Behavior substitution, 8.4 Habit reversal, 9.1 Credible source, 12.5 Adding objects to the environment (BCT n=16) (Clusters n=10)	Intervention group session attendance range n=6 to n=13 (46-100%); median (IQR) = 10 (3.8) participants/session. Control median (IQR) attendance = 6.5 (1.8).
Bickmore, 2013	Tablet, app, pedometers	52	Tablet with embodied conversational agents (ECA) (animated) to motivate participants to do more walking and pedometers	Encouraged to wear pedometers every day and complete monthly logs to track step count	1.2 Problem solving, 2.2 Feedback on behavior, 2.3 Self-monitoring of behavior, 3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 6.1 Demonstration of the behavior, 8.1 Behavioral practice/rehearsal, 10.3 Non-specific reward, 12.5 Adding objects into the environment (BCT n=9) (Clusters n=8)	Intervention interacted with take-home virtual coach an average of 35.8 ± 19.7 times during first 60-days. Decreased after first week (average of 4.7 per week to 4.0) then to 3.3 sessions/week Used waiting room kiosks 1.0 +/- 2.9 times during 10-month period between 2 and 12 months
Broekhuizen,	Website, e-	12	Internet based PA	3 month waiting list	1.1 Goal setting (behavior), 1.3 Goal	Not reported

2016	coach, accelerometer		program. DirectLife - accelerometer based activity monitor, personal website and e-coach		setting (outcome), 1.5 Review behavior goal(s), 2.2 Feedback on behavior, 4.1 Instruction on how to perform the behavior, 9.1 Credible source, 12.5 Adding objects into the environment (BCT n=8) (Clusters n=6)	
Cadmus-Bertram, 2015	Fitbit One and Fitbit website (PA data only)	16	Fitbit One and Fitbit website (PA data only). Asked to perform 150min/week MVPA and walk 10,000 steps/day.	Basic step-counting pedometer, printed materials with tips for increasing steps	1.3 Goal setting (outcome), 1.9 Commitment, 2.3 Self-monitoring of behavior, 12.5 Adding objects into the environment (BCT n=4) (Clusters n=3)	88% used website, 52% logging in 2-3 day/week. 72% viewed tracker data on device 1 time/day). 80% had no computer issues, 80% had no technical difficulty with tracker, 84% no issues with lost/broken tracker.
Cook, 2015	Web-based education	12	HealthyPast50 - web-based multimedia program with information and guidance on major health promotion topics of healthy aging, diet, physical activity, stress management and tobacco use.	Wait-list	3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 5.1 Information about health consequences, 5.3 Information about social and environmental consequences (BCT n=4) (Clusters n=3)	Mean log-ins 4.33 (SD=4.28; range 0-28). Mean minutes in program 102.26 minutes (SD=148.32). Mean number of pages viewed 11.04 (SD=20.08; range 0-120)
Frederix, 2015	Website, accelerometer,	24	Internet based telerehabilitation program,	Centre-based cardiac rehabilitation program only, at	2.2 Feedback on behavior, 3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 5.1	Patients transmitted activity data mean 1.0 (SD=0.3) times/week.

	semiautomatic SMS text messages, emails, dietary telecoaching		accelerometer data and website, semiautomatic SMS texts messaging 1x week, pre-defined exercise goals, emails tailored to helpful services, dietary telecoaching, Plus, 12-week conventional center-based cardiac rehabilitation program, with at least 2 exercise sessions/week, with endurance training, dietitian, psychologist.	least 2 sessions/week, with including endurance training, dietitian, psychologist.	Information about health consequences, 5.3 Information about social and environmental consequences, 8.1 Behavioral practice/ rehearsal (BCT n=6) (Clusters n=5)	
Keogh, 2014	Nintendo Wii Sports (NWS)	8	Nintendo Wii Sports (baseball, boxing, golf, tennis and 10-pin bowling). Participants selected the frequency, duration and type of games they wished to play.	No treatment. Underwent normal activities of daily living	3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior) (BCT n=2) (Clusters n=2)	Mean 30 ± 24 minutes (range 1-105 min) of NWS/week.

King, 2007	Automated computer controlled interactive phone system	78	CHAT - homebased moderate intensity PA program delivered by automated computer controlled interactive telephone system or human advice via telephone.	Weekly health education classes	1.2 Problem solving, 1.3 Goal setting (outcome), 1.4 Action planning, 2.2 Feedback on behavior, 2.3 Self-monitoring of behavior, 3.1 Social support (unspecified), 9.1 Credible source, 12.5 Adding objects into the environment (BCT n=8) (Clusters n=5)	Not reported
King, 2014	Automated computer controlled interactive phone system	26	CHAT - homebased moderate intensity PA program delivered by automated computer controlled interactive telephone system or human advice via telephone.	Weekly health education classes	Follow-up study to King 2007	Not reported
Knight, 2015	Smartphone app (health anywhere), Blackberry Curve 8530, Bluetooth enabled	12	All groups had access to smartphone, app, Bluetooth blood pressure monitor, glucometer with wireless adaptor	n/a	2.3 Self-monitoring of behavior, 2.4 Self-monitoring of outcome(s) of behavior(s), 4.1 Instruction on how to perform the behavior (BCT n=3) (Clusters n=2)	Not reported

	blood pressure monitor, glucometer with polymap wireless adaptor, pedometer		and pedometer. Exercise group: PA prescription targeting increases in high-intensity activity (i.e. exercise). Sedentary behavior group: PA prescription targeting reductions and interruptions in low-intensity daily activity. Comprehensive counselling group: Activity prescription targeting both Exercise and Sedentary behaviors (see above).			
Kullgren, 2014	Fitbit pedometer, automated email/text feedback	24	Financial incentive group: Wore pedometers, automated	Fitbit pedometer. Goal to increase daily steps by 50%. No specific instructions but provided links to	1.1 Goal setting (behavior), 2.2 Feedback on behavior, 3.1 Social support (unspecified) (peer only), 10.1 Material incentive (behavior) (financial only) (BCT n=4) (Clusters n=4)	Posts in Peer network and combined group by individual (median =1 post, range 0-27), and peer group (median 5 posts,

			email/text feedback about how often they met goal. Entry into lottery to win money if met goal Peer network group: wore pedometers, automated email/text feedback about how often met goal. Access to online message board where they could communicate with 4 other participants. Combined group: Used both financial and peer network intervention simultaneously	National Institutes of Health information on exercise and walking.		range 0-71). 47% never posted a message.
Leutwyler, 2015	Xbox 360 Kinect	6	Kinect Xbox 360 for 30min once a week. Most often played games were bowling,	n/a	3.1 Social support (unspecified), 8.1 Behavioral practice/ rehearsal, 12.5 Adding objects into the environment (BCT n=3) (Clusters n=3)	Mean number of groups attended 5.6 out of 6 (SD=0.8). Mean total minutes attended 169 out of 180

			dance, carnival games, skiing, tai chi, baseball, darts, golf, river rafting and 20,000 leaks under the sea. Groups of 3-4			(SD=23.7) 70% (n=14) perfect attendance.
Lyons, 2017	Jawbone Up24, Jawbone Up app on iPad mini	12	Jawbone Up24 and app. Weekly telephone behavioral counselling.	Wait-list	1.1 Goal setting (behavior), 1.2 Problem solving, 1.4 Action planning, 1.5 Review behavior goal(s), 1.6 Discrepancy between current behavior and goal, 1.9 Commitment, 2.2 Feedback on behavior, 2.3 Self-monitoring of behavior, 3.1 Social support (unspecified), 3.3 Social support (emotional), 4.1 Instruction on how to perform the behavior, 4.2 Information about antecedents, 5.1 Information about health consequences, 5.3 Information about social and environmental consequences, 5.4 Monitoring of emotional consequences, 5.6 Information about emotional consequences, 6.2 Social comparison, 7.1 Prompts/ cues, 8.2, Behavior substitution 9.1 Credible source, 10.4 Social reward, 12.5 Adding objects into the environment, 15.3 Focus on past success (BCT n=23) (Clusters n=12)	Mean of 10.2 (SD=2.4) of 12 counselling calls Wore Up24 monitors mean 81.85 (SD=3.73) of 90 days 5 Up24 monitors reported broken, 1 lost, and replaced.
Müller, 2016	SMS text messaging	12	Exercise booklet and SMS text messaging (instructions to	Exercise booklet only.	2.2 Feedback on behavior, 4.1 Instruction on how to perform the behavior, 6.1 Demonstration of the behavior, 7.1 Prompts/ cues, 8.1 Behavioral practice/	50% read all 60 SMS messages 39% ignored SMS messages after some time

			exercise, rewards/praise)		rehearsal, 10.3 Non-specific incentive (BCT n=6) (Clusters n=6)	
Nguyen, 2009	Mobile Coaching, pedometer	12	Information entered on mobile phone and was praised and encouraged by e-coach when desired behavior performed	Entered information on mobile phone. No e-coach.	1.2 Problem solving, 2.2 Feedback on behavior, 2.3 Self-monitoring of behavior, 2.4 Self-monitoring of outcome(s) of behavior, 3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 6.1 Demonstration of the behavior, 7.1 Prompts/ cues, 9.1 Credible source, 12.5 Adding objects into the environment (BCT n=10) (Clusters n=8)	MOBILE-C 87% submitted exercise and symptom data MOBILE-SM 66% submitted exercise and symptom data
O'Brien, 2015	Nike Fuel Band	12	Nike Fuel band, document steps and calories on paper diary (no access to computer/smartphone), plus weekly 45min session on strategies to change PA and nutrition, plus 30min group walking session each week led by researcher	n/a	1.2 Problem solving, 2.3 Self-monitoring of behavior, 2.4 Self-monitoring of outcome(s) of behavior, 4.1 Instruction on how to perform the behavior, 8.1 Behavioral practice/ rehearsal, 12.5 Adding objects into the environment (BCT n=6) (Clusters n=5)	Not reported
Ruiz, 2012	Virtual reality	8	10 min VR session weeks 0, 2 and 4. Virtual representation of the physical self	VR without avatar just static graphics depicting the PA routine. Plus, 10min presentation about	4.1 Instruction on how to perform the behavior, 6.1 Demonstration of the behavior, 8.1 Behavioral practice/ rehearsal, 12.5 Adding objects into the environment	Not reported

			(VRS) exercising condition with an avatar resembling the subjects' heads, or Virtual representation of other (VRO) exercising condition with an avatar featuring an unknown person's head of the same sex, skin color and approximately same age. Plus, 10min presentation about basic principles of PA and instructions how to perform different types of exercise.	basic principles of PA and instructions how to perform different types of exercise.	(BCT n=4) (Clusters n=4)	
Strand, 2014	Nintendo Wii Active	24	LIFE Program - Wii active onsite exergaming (8wks) lead by younger adult trainers (aged 19-26 years) 2x week. Then newsletter	n/a	3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 6.1 Demonstration of the behavior, 8.1 Behavioral practice/ rehearsal, 12.5 Adding objects into the environment (BCT n=5) (Clusters n=5)	Not reported

			intervention for following 16wks			
Tiedemann, 2015	Telephone coaching, Fitbit	12	Fall prevention strategies, telephone health-based coaching, Fitbit	n/a	1.3 Goal setting (outcome), 2.3 Self-monitoring of behavior, 3.1 Social support (unspecified), 9.1 Credible source, 12.5 Adding objects into the environment (BCT n=5) (Clusters n=5)	All participants used the Fitbit enhanced pedometer and synchronized it at least once//week with internet-based software
Vidoni, 2016	Fitbit Zip and coach	16	Fitbit Zip unmasked. Telephone coach biweekly, exercise prescription booklet	Delayed start. Fitbit Zip masked weeks 1-8. Completed intervention in week 9-16.	1.1 Goal setting (behavior), 1.2 Problem solving, 2.3 Self-monitoring of behavior, 3.1 Social support (unspecified), 12.5 Adding objects into the environment (BCT n=5) (Clusters n=4)	Not reported
Wijsman, 2013	Website, e-coach, accelerometer	12	Internet based PA program - DirectLife - accelerometer based activity monitor, personal website and e-coach	3-month wait-list	1.1 Goal setting (behavior), 1.3 Goal setting (outcome), 1.5 Review behavior goal(s), 2.2 Feedback on behavior, 4.1 Instruction on how to perform the behavior, 9.1 Credible source, 12.5 Adding objects into the environment (BCT n=8) (Clusters n=6)	Intervention group: 91.2% (104/114) completed 12-week program
Williams, 2016	Nintendo Wii Sports	6	Nintendo Wii Sports (tennis, bowling or golf as they allow 4 players to play simultaneously). 45min session including 15min educational component based	n/a	1.1 Goal setting (behavior), 3.1 Social support (unspecified), 4.1 Instruction on how to perform the behavior, 6.1 Demonstration of the behavior, 8.1 Behavioral practice/ rehearsal, 12.5 Adding objects into the environment (BCT n=6) (Clusters n=6)	Average number sessions attended 9.67. 25% participants (n=6) attended all 12 sessions

	on Go4Life. Bi-weekly sessions	

*In relation to BCT Taxonomy v1 (Michie et al., 2013)

**Individualized intervention duration. Range provided.

Table 3 Outcome measures for studies included

Author, year	Physical Activity outcome Measures	Sedentary Behavior outcome measures	Other outcomes measured	Confounding Variables	Risk of bias
Ashe, 2015	PA min/day Steps/day	% time/day	BMI, weight, SBP, DBP, Behavior intentions, exercise self-efficacy, self-rated health, social support	Education, employment, baseline measures	Low
Bickmore, 2013	Steps/day	n/a	None	Sex, literacy category, clinic location, average steps per day during days 1-13 (baseline)	Medium
Broekhuizen, 2016	Change in PA in relation to QoL measures	n/a	Height, weight, BMI, functioning (physical/ social), role limitations (physical/ emotional) emotional/ mental health, vitality, pain, general health perception, health change, total RAND-36 score	Age, sex, BMI	Medium
Cadmus-Bertram, 2015	PA min/week Steps/day Bouts of MVPA Bouts of Light PA	n/a	Technology use, weight, BMI	Age, weartime	Medium
Cook, 2015	Steps/day Change in IPAQ scores	SB min/week	Diet, BMI, symptoms of distress, coping with stress, aging beliefs	Gender, age, race, marital status, education, income	Medium
Frederix, 2015	PA min/day	n/a	VO2 peak, HR max, Watts, Watts (pred%), first ventilatory threshold (Watts and bpm), oxygen uptake efficiency slope, weight, BMI, DBP, SBP, Heart-	None mentioned	Medium

			QoL		
Keogh, 2014	PA min/day Energy expenditure MVPA days/week	n/a	Functional performance, QoL	None mentioned	Low
King, 2007	Steps/day	n/a	None	Adjusted for 12-month measures	Medium
King, 2014	Steps/day	n/a	PAR energy expenditure, PAR days/week engaged in 30min or more MVPA, CHAMPS energy expenditure, CHAMPS mins of MVPA, CHAMPS times/week engaged in 30min or more MVPA	Baseline adjusted	Medium
Knight, 2015	Stepping time min/day Steps/day	n/a	Weight, SBP, DBP, blood glucose	Age, sex, group assignment	Low
Kullgren, 2014	Change in steps/day Number of days walking goals met	n/a	None	Household residents, education, employment status, annual household income, race/ethnicity, health status, motivation to increase walking, relative autonomy index	Medium
Leutwyler, 2015	Change in PA (Number of participants)	Change in sedentary hours (Number of participants)	None	Smoking status, residence, race	Low
Lyons, 2017	PA min/day Steps/day	SB min/day	Body fat %, weight, fitness	Cohort,	Low
Müller, 2016	PA related energy	SB hours/day (change	Exercise self-efficacy score,	None mentioned	Medium

	expenditure (MET-min per week)	in)	BMI, grip strength, lower body strength (repetitions in 30sec chair stand test)		
Nguyen, 2009	Steps/day % time in moderate-high activity steps/min	% time/day	Incremental cycle test, six-minute walk, peak performance, changes in health-related QoL	None mentioned	Medium
O'Brien, 2015	Steps/day	n/a	BMI, WC, SBP, DBP, HR, timed up and go	No confounders adjusted for. Race, Marital status, income, education	Low
Ruiz, 2012	PA related energy expenditure (Kcal/day	n/a	Self-efficacy	None mentioned	Medium
Strand, 2014	Change in self-report PA (Number of participants)	n/a	Perceived physical wellness, program evaluation, successful program site characteristics	None adjusted for. Measured = Ethnicity (white, non-white), general health, marital status, living arrangement, contact with youth in a day physical activity participation	Low
Tiedemann, 2015	Steps/day	n/a	None	No confounders adjusted for. Lives alone, English spoken at home, accommodation type, total medications, total co-morbidities, fallen in past year, number of risk factors identified, self-rated balance fair/poor, self-rated fear of falling ≥moderate.	Low

Vidoni, 2016	Steps/week	n/a	Mini physical performance test, 6-min walk (yards), QoL-AD, Self-efficacy	None mentioned	Medium
Wijsman, 2013	Change in PA min/day	n/a	Weight, BMI, HC, WC, waist/hip ratio, fat %, lean mass, SBP, DBP, HR, grip strength, Framingham 10-year CVD risk %, fasting glucose venous, fasting insulin, HbA1c, HOMA, TC, HDL, Ln triglyceride, LDL, TC:HDL ratio, Ln C-reactive protein	None adjusted for. Measured = degree of self-reported PA, education, smoking, alcohol use, medical history and medication use	Medium
Williams, 2016	RAPA Scores	n/a	Barriers to exercise, self-efficacy, benefits of exercise	None mentioned	Low

WC, waist circumference; SBP, systolic blood pressure; DBP, diastolic blood pressure, HR, heart rate; HDL, high-density lipoprotein cholesterol; LDL, low-density lipoprotein cholesterol; QoL, quality of life; TC, total cholesterol; HC, hip circumference; HOMA, homeostatic model assessment.

Table 4 Meta-analysis of effects of DBCIs on physical activity and total sedentary time

Analysis	No. studies	No. participants	SMD	Meta-analysis 95% CI		P value	Between group P value	No. studies	MD	Meta-analysis 95% CI		P value	Heterogeneity Q	Heterogeneity P value	Heterogeneity I^2	Publication Bias Kendal l's Tau	Publication Bias P value	Publication Bias Egger intercept	Publication Bias P Value	Trim and fill analysis Effect size (95% CI) [Number studies trimmed]
Total PA																				
Study Design																				
RCTs (EI)	8	450	**0.28**	**0.01**	**0.56**	**0.04**		n/a	n/a	n/a	n/a	n/a	18.86	0.04	46.98	0.33	0.16	1.99	0.11	0.25 (0.07, 0.44) [1]
RCTs (FU)	2	255	0.11	-0.14	0.36	0.39	**0.05**	n/a	n/a	n/a	n/a	n/a	0.51	0.92	0.00	0.17	0.73	1.65	0.04	0.05 (-0.16, 0.26) [2]
Pre-post	6	159	**0.25**	**0.09**	**0.41**	**0.002**	n/a	n/a	n/a	n/a	n/a	n/a	11.04	0.14	36.60	0.04	0.90	-0.70	0.75	Unchanged
PA Measure																				
Objective RCT (EI)	7	476	0.28	-0.02	0.06	0.07		n/a	n/a	n/a	n/a	n/a	18.69	0.03	51.83	0.31	0.21	1.98	0.15	0.24 (0.05, 0.42) [1]
Subjective RCT (EI)	1	39	0.36	-0.27	1.00	0.27	**0.03**	n/a	n/a	n/a	n/a	n/a	0.00	1	0.00	n/a	n/a	n/a	n/a	n/a
Objective Pre-post	4	122	**0.24**	**0.02**	**0.45**	**0.03**		n/a	n/a	n/a	n/a	n/a	10.28	0.07	51.36	0.00	1.00	-1.37	0.62	Unchanged
Subjective Pre-post	2	37	**0.27**	**0.02**	**0.53**	**0.04**	**0.003**	n/a	n/a	n/a	n/a	n/a	0.75	0.39	0.00	n/a	n/a	n/a	n/a	n/a
BCT Clusters																				
≥ 3 Pre-post	4	101	**0.37**	**0.21**	**0.53**	**<0.001**	**<0.001**	n/a	n/a	n/a	n/a	n/a	2.48	0.48	0.00	0.17	0.73	1.27	0.58	0.35 (0.20, 0.50) [1]
1-2 Pre-post	2	21	0.09	-0.14	0.32	0.44		n/a	n/a	n/a	n/a	n/a	3.84	0.28	21.93	0.83	0.09	18.34	<0.01	Unchanged
Steps																				
Study Design																				
RCTs (EI)	6	383	0.18	-0.03	0.38	0.09		6	401	-125	926	0.13	0.17	0.68	0.00	0.29	0.19	1.24	0.13	0.19 (-0.005, 0.39) [1]
RCTs (FU)	2	255	0.11	-0.14	0.36	0.39	0.06	2	280	-508	1068	0.49	6.03	0.87	0.00	n/a	n/a	n/a	n/a	n/a
Pre-post	3	122	-0.20	-0.42	0.02	0.08	n/a	3	**-737**	**-1361**	**-113**	**0.02**	8.61	0.07	53.55	0.10	0.81	6.09	0.51	-0.34 (-0.59, -

																			0.10) [2]
BCT Clusters																			
≥ 3	2	77	**-0.41**	**-0.60**	**-0.22**	**<0.001**		2	**-1194**	**-1727**	**-662**	**<0.001**	0.34	0.56	0.00	n/a	n/a	n/a	n/a	n/a
Pre-post																				
1-2	1	45	0.12	-0.22	0.24	0.95	**0.002**	1	25	-862	911	0.96	0.82	0.66	0.00	-0.67	0.30	-19.05	0.02	Unchanged
Pre-post																				
MVPA																				
Study Design																				
RCT (EI)	6	694	**0.47**	**0.32**	**0.62**	**<0.001**	n/a	3	**51.97**	**23.91**	**80.03**	**<0.001**	3.10	0.80	0	-0.43	0.23	-0.39	0.63	Unchanged
PA Measure																				
Objective RCT (EI)	5	443	**0.53**	**0.34**	**0.72**	**<0.001**		5	10.14	-2.33	22.61	0.11	0.93	0.33	0	0.00	1	2.48	0.01	Unchanged
Subjective RCT (EI)	1	251	**0.38**	**0.13**	**0.63**	**<0.001**	**<0.001**	**1**	**49.71**	**17.17**	**82.26**	**0.003**	3.10	0.80	0	n/a	n/a	n/a	n/a	n/a
Total SB																				
Study Design																				
RCT (EI)	5	255	**-0.44**	**-0.69**	**-0.19**	**<0.001**	n/a	3	**-58.49**	**-100.34**	**-16.64**	**<0.001**	1.54	0.82	0	0.10	0.81	0.53	0.54	-0.47 (-0.72, -0.23) [1]
SB Measure																				
Objective RCT (EI)	4	216	**-0.45**	**-0.72**	**-0.17**	**0.001**		4	-33.47	-90.63	23.70	0.25	0.02	0.90	0	0.10	0.81	0.53	0.54	-0.49 (-0.75, -0.23) [1]
Subjective RCT (EI)	1	39	-0.40	-1.04	0.23	0.22	**<0.001**	1	-0.76	-1.95	0.43	0.21	1.54	0.82	0	n/a	n/a	n/a	n/a	n/a

SMD, standardized mean differences; MD, mean differences; PA, physical activity; (EI) End Intervention; (FU) Follow Up; MVPA, moderate-vigorous physical activity; Total SED, total sedentary time; RCT, randomized control trial.

Heterogeneity and publication bias scores based on standardized mean differences

p ≤ 0.05 in bold

Table 5 Meta-analysis of effects of DBCIs on weight, blood pressure and physical functioning in RCT studies

Analysis	No. Studies	No. participants	Meta-analysis SMD	95% CI		P value	No. Studies	Meta-analysis MD	95% CI		P value	Heterogeneity Q	P value	I^2	Publication bias Kendall's Tau	P value	Egger intercept	P value	Trim and fill analysis Effect size (95% CI) [Number studies trimmed]
Weight	5	466	-0.15	-0.33	0.03	0.10	5	-0.68	-3.45	2.09	0.63	1.71	0.79	0	-0.10	0.81	0.47	0.59	-0.26 (-0.40, -0.11) [3]
SBP	3	375	-0.14	-0.35	0.07	0.18	2	**-11.33**	**-21.96**	**-0.71**	**0.04**	2.09	0.35	4.19	0.00	1	-1.70	0.39	-0.03 (-0.27, 0.21) [2]
DBP	3	375	-0.10	-0.30	0.09	0.30	2	-3.04	-9.00	2.93	0.32	1.80	0.40	0	0.00	1	-1.55	0.40	-0.07 (-0.30, 0.16) [1]
Physical functioning	5	451	**0.21**	**0.03**	**0.40**	**0.03**	n/a	n/a	n/a	n/a	n/a	3.69	0.45	0.00	0.30	0.46	0.78	0.47	0.19 (0.005, 0.37) [1]
QoL	3	372	0.27	-0.02	0.57	0.07	n/a	n/a	n/a	n/a	n/a	3.22	0.20	37.92	0.00	1	1.91	0.46	0.09 (-0.08, 0.26) [2]

SMD, standardized mean difference; MD, mean difference; RCT, randomized control trial; kg, kilograms; SBP, systolic blood pressure; DBP, diastolic blood pressure; QoL, quality of life.

Heterogeneity and publication bias scores based on standardized mean differences

Mean differences for SBP and DBP based on 2 studies (159 participants) as Wijsman et al. (2013) automatically removed from model.

p ≤ 0.05 in bold

Table 6 Meta-regression analysis for moderators in RCT (EI) studies on total physical activity

Moderator	Coefficient	95% Confidence Interval		P value	r^2
		Lower	Upper		
Number BCT	0.04	-0.43	0.08	0.08	0.24
PA measurement	0.08	-0.89	1.04	0.88	0.00
Mean age	-0.04	-0.09	0.02	0.20	0.06
% males	-0.005	-0.16	0.007	0.43	0.00
Publication year	0.10	-0.56	0.26	0.21	0.07
Region	0.08	-0.90	1.04	0.88	0.00
Setting	-0.21	-1.07	0.66	0.64	0.00
Duration	0.06	-0.02	0.13	0.12	0.00

BCT, behavior change technique; PA, physical activity. PA measurement (objective/ subjective); Region (North America/ non-North America); Setting (community based/ non-community based).

$p \leq 0.05$ in bold

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Appendix

Appendix A – Search terms

The key word terms used were: (physical activity OR walking OR exercise OR sedentary* OR sedentary behavio* OR sitting) and (older adult* OR aged OR aging OR ageing OR over 50 OR elderly) and (digital behavio* OR digital intervention* OR wearable electronic device* OR fitness tracker* OR fitbit* OR activity tracker* OR fitness tracker* OR ehealth OR mhealth OR video game* OR wii OR xbox OR virtual realit* OR exergam* or mobile phone* or augmented realit*).

Appendix B – JBI Critical appraisal checklist for randomized controlled trials

JBI Critical Appraisal Checklist for Randomized Controlled Trials

Reviewer_____ Date_____

Author_____ Year_____ Record Number _____

		Yes	No	Unclear	NA
1.	Was true randomization used for assignment of participants to treatment groups?	☐	☐	☐	☐
2.	Was allocation to treatment groups concealed?	☐	☐	☐	☐
3.	Were treatment groups similar at the baseline?	☐	☐	☐	☐
4.	Were participants blind to treatment assignment?	☐	☐	☐	☐
5.	Were those delivering treatment blind to treatment assignment?	☐	☐	☐	☐
6.	Were outcomes assessors blind to treatment assignment?	☐	☐	☐	☐
7.	Were treatment groups treated identically other than the intervention of interest?	☐	☐	☐	☐
8.	Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed?	☐	☐	☐	☐
9.	Were participants analyzed in the groups to which they were randomized?	☐	☐	☐	☐
10.	Were outcomes measured in the same way for treatment groups?	☐	☐	☐	☐
11.	Were outcomes measured in a reliable way?	☐	☐	☐	☐
12.	Was appropriate statistical analysis used?	☐	☐	☐	☐
13.	Was the trial design appropriate, and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?	☐	☐	☐	☐

Overall appraisal: Include ☐ Exclude ☐ Seek further info ☐

Comments (Including reason for exclusion)

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Appendix C – JBI Critical appraisal checklist for quasi-experimental studies

JBI Critical Appraisal Checklist for Quasi-Experimental Studies (non-randomized experimental studies)

Reviewer_____Date_____

Author _____Year_____Record Number _____

	Yes	No	Unclear	Not applicable
14. Is it clear in the study what is the 'cause' and what is the 'effect' (i.e. there is no confusion about which variable comes first)?	☐	☐	☐	☐
15. Were the participants included in any comparisons similar?	☐	☐	☐	☐
16. Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	☐	☐	☐	☐
17. Was there a control group?	☐	☐	☐	☐
18. Were there multiple measurements of the outcome both pre and post the intervention/exposure?	☐	☐	☐	☐
19. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed?	☐	☐	☐	☐
20. Were the outcomes of participants included in any comparisons measured in the same way?	☐	☐	☐	☐
21. Were outcomes measured in a reliable way?	☐	☐	☐	☐
22. Was appropriate statistical analysis used?	☐	☐	☐	☐

Overall appraisal: Include ☐ Exclude ☐ Seek further info ☐

Comments (Including reason for exclusion)

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Appendix D – JBI Critical appraisal checklist results

	Ashe, 2015	Bickmore, 2013	Broekhuizen, 2016	Caamus-Bertram, 2015	Cook, 2015	Frederix, 2015	Keogh, 2014	King, 2007	King, 2014	Knight, 2015	Kullgren, 2014	Leutwyler, 2015	Lyons, 2017	Müller, 2016	Nguyen, 2009	O'Brien, 2015	Ruiz, 2012	Strand, 2014	Tiedemann, 2015	Vidoni, 2016	Wijsman, 2013	Williams, 2016
Rank (High, Medium, Low)	M	H	M	M	M	M	L	M	M	L	M	L	M	M	M	L	H	L	L	H	M	L
Question number																						
RCT Studies																						
1	Y	N	N	N	Y	Y		N	N		Y		Y	N	N		?			?	N	
2	Y	N	Y	?	N	Y		?	?		N		Y	Y	Y		?			Y	Y	
3	N	Y	Y	Y	Y	Y		Y	Y		N		Y	Y	?		Y			N	Y	
4	N	?	?	Y	N	?		?	?		N		N	N	N		?			N	?	
5	N	N	N	?	N	N		?	?		?		N	N	N		?			N	N	
6	Y	?	?	?	?	Y		Y	Y		Y		N	N	Y		?			?	?	
7	Y	Y	Y	Y	Y	?		Y	Y		Y		Y	Y	Y		?			Y	Y	
8	Y	Y	Y	Y	Y	Y		Y	Y		Y		Y	Y	Y		Y			Y	Y	
9	Y	Y	Y	Y	Y	Y		Y	Y		Y		Y	Y	Y		Y			Y	Y	
10	Y	Y	Y	Y	Y	Y		Y	Y		Y		Y	Y	Y		Y			Y	Y	
11	Y	Y	Y	Y	Y	Y		Y	Y		Y		Y	Y	Y		Y			Y	Y	
12	Y	Y	Y	Y	Y	Y		Y	Y		Y		Y	Y	Y		Y			Y	Y	
13	Y	Y	Y	Y	Y	Y		Y	Y		Y		Y	Y	Y		Y			Y	Y	

Quasi-Experimental													
14		Y		Y		Y		Y		Y	Y		Y
15		Y		Y		Y		Y		Y	Y		Y
16		Y		Y		Y		Y		Y	Y		Y
17		Y		N		N		N		N	N		N
18		Y		Y		Y		Y		Y	Y		Y
19		Y		Y		Y		Y		Y	Y		Y
20		Y		Y		Y		Y		Y	Y		Y
21		Y		Y		Y		Y		Y	Y		Y
22		Y		Y		Y		Y		Y	Y		Y

Y = yes; N = no; ? = unclear; n/a = not applicable

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Highlights

- The present review found that digital behavior change interventions have potential to increase physical activity and reduce sedentary time in older adults
- The review also found that digital behavior change interventions targeting physical activity and sedentary time may improve physical functioning and reduced systolic blood pressure
- The most common behavior change techniques embedded in the digital behavior change interventions included: social support, goal setting and feedback
- A Minimum of 3 behavior change technique clusters were required for significant effects on physical activity