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Review

# Alexa, let's train now! — A systematic review and classification approach to digital and home-based physical training interventions aiming to support healthy cognitive aging

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## Abstract

*Background*: There is mounting evidence that regular physical activity is an important prerequisite for healthy cognitive aging. Consequently, the finding that almost one-third of the adult population does not reach the recommended level of regular physical activity calls for further public health actions. In this context, digital and home-based physical training interventions might be a promising alternative to center-based intervention programs. Thus, this systematic review aimed to summarize the current state of the literature on the effects of digital and home-based physical training interventions on adult cognitive performance.
*Methods*: In this pre-registered systematic review (PROSPERO; ID: CRD42022320031), 5 electronic databases (PubMed, Web of Science, PsycInfo, SPORTDiscus, and Cochrane Library) were searched by 2 independent researchers (FH and PT) to identify eligible studies investigating the effects of digital and home-based physical training interventions on cognitive performance in adults. The systematic literature search yielded 8258 records (extra 17 records from other sources), of which 27 controlled trials were considered relevant. Two reviewers (FH and PT) independently extracted data and assessed the risk of bias using a modified version of the Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX scale).
*Results*: Of the 27 reviewed studies, 15 reported positive effects on cognitive and motor-cognitive outcomes (i.e., performance improvements in measures of executive functions, working memory, and choice stepping reaction test), and a considerable heterogeneity concerning study-related, population-related, and intervention-related characteristics was noticed. A more detailed analysis suggests that, in particular, interventions using online classes and technology-based exercise devices (i.e., step-based exergames) can improve cognitive performance in healthy older adults. Approximately one-half of the reviewed studies were rated as having a high risk of bias with respect to completion adherence (≤85%) and monitoring of the level of regular physical activity in the control group.
*Conclusion*: The current state of evidence concerning the effectiveness of digital and home-based physical training interventions is mixed overall, though there is limited evidence that specific types of digital and home-based physical training interventions (e.g., online classes and step-based exergames) can be an effective strategy for improving cognitive performance in older adults. However, due to the limited number of available studies, future high-quality studies are needed to buttress this assumption empirically and to allow for more solid and nuanced conclusions.

**Keywords:** Brain; Cognition; Digital health; Exercise-cognition; Physical activity

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## 1. Introduction

It is well-documented that higher levels of physical activity (e.g., typically engendered through physical training) and physical fitness (e.g., cardiorespiratory fitness) are associated with better brain health and cognitive performance in adults.[1−16] Thus, a physically active lifestyle is strongly recommended to prevent or at least delay the onset of age-associated neurological diseases such as dementia.[17−19] However, though the above-mentioned evidence strongly corroborates the idea that a physically active lifestyle across the lifespan is an important prerequisite for healthy cognitive aging, the practical implementation of regular physical activity (e.g., in form of physical training) remains very challenging, as indicated by the large number of adults who do not achieve the recommended level of regular physical activity.[20−23] More specifically, almost one-third of the adult population (i.e., the global age-standardized prevalence of ∼27.5%[21,24]) can be classified as physically inactive since they do not achieve the level of physical activity[20,21,23] recommended by the World Health Organization.[24−26] There is also evidence that the prevalence of physical inactivity increases with age[23,27,28] and/or the worsening of cognitive status.[29] Given the high worldwide prevalence of physical inactivity in the adult population,[21,24] especially among older and cognitively impaired adults,[29] and the substantial societal and economic costs of physical inactivity,[30] there is a need for developing efficient intervention strategies to counteract the detrimental effects of physical inactivity on cognition.

In this context, we propose that home-based interventions utilizing digital technologies to deliver structured forms of physical activity (i.e., physical exercise and physical training) harbor great potential as they combine the strengths that come with both home-based training and the utilization of digital technologies.[31] In particular, home-based physical training interventions offer an advantage in that they circumvent or at least attenuate 2 main barriers that frequently hinder adults, regardless of age or pathologies, from engaging in structured forms of physical activity: lack of opportunity (e.g., no way to access a training facility or health intervention program) and lack of time (e.g., no way to commute to a training facility).[32−45] Moreover, home-based intervention programs can better reach adults for whom no appropriate intervention program is available based on their specific living conditions (e.g., those who are unable to drive a car), their diseases (e.g., stroke), or due to challenging life situations (e.g., home confinement during a pandemic). This allows them to benefit from the positive effects of physical training interventions, which include benefits to cognitive performance. This idea is reinforced by evidence suggesting that home-based interventions using digital technologies demonstrate a similar effectiveness (with respect to physical outcomes) and are less costly than center-based and face-to-face intervention programs.[46−48] In this regard, the utilization of digital technologies to remotely deliver a physical training intervention is a crucial element that provides practical advantages compared to non-digital solutions (e.g., written manuals). In particular, digital technologies (a) allow for better visualization of how the exercise should be conducted (e.g., due to video instructions); (b) enable real-time (synchronous) and decoupled (asynchronous) communication with participant(s) (e.g., via videoconference software or video capsules), which is needed to provide adequate feedback (e.g., on proper exercise execution); and (c) allow for a "gamification" of exercise programs, which motivates participants to do physical exercises when they are not being supervised.[49] Furthermore, there is evidence that it is safe and feasible to utilize digital technologies (e.g., videoconference software or Apps) to deliver home-based training interventions to older community-dwelling adults.[50−52] Moreover, older community-dwelling adults show a high attendance adherence to these interventions (> 85%)[50−52] and a willingness to participate in such physical training programs in the future.[50,52]

Taken together, digital and home-based physical training interventions can be a promising alternative to traditional and center-based physical training interventions.[31,53] However, the literature concerning the effects of digital and home-based physical training interventions on cognitive performance has not been systematically summarized because available reviews tend to (a) focus on only a single type of home-based physical training intervention (i.e., exergames),[54,55] (b) investigate only the effects on motor outcomes (i.e., balance and gait) and health-related quality of life,[54−58] and/or (c) consider only special cohorts (e.g., older adults with neurological diseases).[54,55,59] To provide an updated and comprehensive overview of the current state of the literature, the aim of this systematic review was to summarize and discuss studies investigating the effects of digital and home-based physical training interventions on measures of cognitive performance in the adult population (see the Methods section for a more detailed definition and description). In particular, based on a systematic literature search in several electronic databases, this review aimed to (a) evaluate the characteristics of the digital and home-based physical training interventions (e.g., exercise and training variables, and implementation of their delivery), (b) qualitatively analyze the effectiveness of digital and home-based physical training interventions on cognitive outcome measures, (c) assess the safety and feasibility of digital and home-based training interventions by examining intervention-related measures of adherence and the occurrence of adverse events, (d) identify research gaps in the available literature, and (e) provide recommendations for further investigations in this research field.

## 2. Methods

This systematic review was conducted in line with the recommended reporting items for systematic reviews and meta-analysis (as specified in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, see Supplementary material−PRISMA checklist and abstract checklist)[60−62] and was preregistered in the International Prospective Register Of Systematic Reviews (PROSPERO; ID: CRD42022320031). We based the search strategy on the participants, intervention, comparisions, outcomes, and study decision (PICOS) worksheet for systematic reviews.[63]

### 2.1. Search strategy and process

In accordance with established guidelines for systematic reviews,[60] the literature search was conducted by 2 independent researchers (FH and PT) on June 24, 2022 using the following 5 electronic databases (applied filters): PubMed (all fields), Web of Science (title), PsycInfo (all text), SPORTDiscus (all text), and Cochrane Library (all text; category Trials). Thereto, relevant terms were combined to the create a search string. See details in Supplementary material—PICOS worksheet.

### 2.2. Inclusion and exclusion criteria

As recommended by established guidelines,[60–62,64] we defined standarized inclusion and exclusion criteria based on the following items: Participants, Intervention, Comparisons, Outcomes, and Study design (also referred to as the PICOS-principle). The inclusion and exclusion criteria are provided in more detail in Supplementary material—PICOS worksheet.

### 2.3. Types of digital and home-based physical training interventions

From a conceptual view, digital and home-based physical training interventions can be broadly categorized based on the differences concerning the mode of interaction being influenced by the technical implementation and the degree of supervision inherent to the intervention.

The mode of interaction can be differentiated based on proximity to the time of the interaction. Thereto, the terms synchronous and asynchronous (also known as "store-and-forward") are commonly used in the literature.[65–69]

- Synchronous refers to an interaction that occurs at the same time (e.g., real-time interaction via videoconference).[65–69] Thus, synchronous interactions provide the advantage of an immediate exchange of information (e.g., feedback on the correct execution of a specific physical exercise) but on the downside may limit time flexibility.[66,68]
- Asynchronous refers to an interaction that occurs at different times (e.g., decoupled interaction via video recordings).[65–69] Hence, an asynchronous interaction allows for an time-flexible exchange of information at the convenience of the participating parties (e.g., physical training on demand due to video capsules) but suffers from a disadvantage in that the information might be misinterpreted (e.g., wrong execution of the physical exercises).[68]

Also, the literature distinguishes 3 different categories of supervision: direct supervision, general supervision, and no supervision.[70]

- Direct supervision refers to the live monitoring of each exercise session either in person or virtually by a health care professional (e.g., via sensors that track movements and physiological changes), which allows for immediate support and feedback on the proper execution of an exercise.[70]
- General supervision (also referred to as "facilitated") is characterized by a regular in-person or virtual contact with a health care professional to support the trainee and/or adopt, if necessary, the exercise and training prescription.[70] However, general supervision does not include direct supervision of each exercise session.[70]
- No supervision (also referred to as "unsupervised") means the trainee has no direct contact with a health care professional throughout the intervention period (except for the pre- and post-assessment).

Since the differences concerning the mode of interaction and degree of supervision are both related to technological implementation, we propose that digital and home-based physical training interventions can be broadly categorized into 3 categories: digital databases, online classes, and technology-based exercise devices (Fig. 1). We recommend avoiding use of the term "web-based" without specifying the level of supervision because it is ambiguous and can refer to physical interventions using digital databases (e.g., YouTube—low level of direct supervision) and/or online classes (e.g., via Zoom—relatively high level of direct supervision). Furthermore, we wish to acknowledge that the appropriate level of supervision

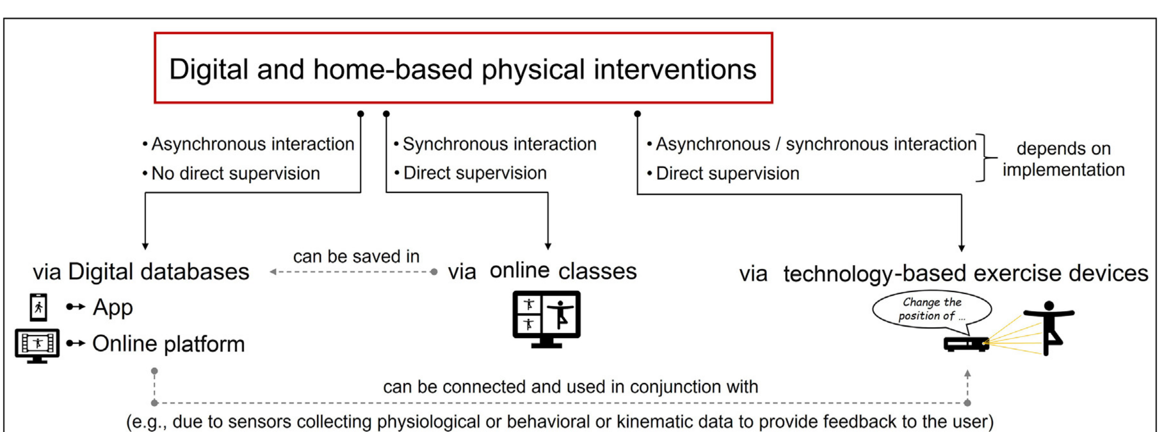


Fig. 1. Schematic illustration of the proposed classification approach to digital and home-based physical interventions. App = application.

depends on several factors (e.g., health status, previous experience with physical exercises, and the complexity of the physical exercises). In our classification framework, supervision differentiates between types of digital and home-based physical training interventions and is not a criterion to rate whether a particular type of digital and home-based physical training is suitable for a certain population and/or intervention.

What follows are our definitions for the different types of digital and home-based physical interventions, namely, (a) digital databases, (b) online classes, and (c) technology-based exercise devices.

(a) Digital and homed-based physical interventions utilizing digital databases rely on the storage of instructions (e.g., via video capsules) on specific digital media (e.g., smartphone or tablet-based Apps, video capsules on YouTube, Facebook, or DVDs. Digital databases are characterized by a relatively low level of direct supervision but provide advantages in that they can be delivered to a relatively large number of individuals and they allow for on-demand training (i.e., asynchronous interaction).

(b) Online classes cover the digital and home-based physical interventions in which single exercise sessions are provided in real-time by, for instance, an exercise professional (e.g., exercise and sports scientist, physiotherapist) via software that allows for remote communication (e.g., video conference software such as Zoom or Facebook Live). Due to the synchronous interaction (i.e., real-time communication) of the exercise professional and trainee(s) via videoconference software, online classes are characterized by a relatively high level of direct supervision. However, due to the synchronous interaction, online classes are limited with respect to time flexibility and number of attendees (e.g., to ensure an appropriate level of direct supervision).

(c) Technology-based exercise devices refers to a wide range of technology-based and digital solutions, including devices to remind individuals to be physically active (e.g., wearables such as smartwatches) and devices used directly for physical exercises (e.g., virtual-reality-enhanced stationary ergometer). In this review article, we focus on technology-based exercise devices that can be used to conduct and/or prescribe a physical intervention in real-time rather than solely monitor health-related parameters. These devices include but are not limited to exergames (a portmanteau consisting of the terms physical exercise and gaming[71]). In other words, the term exergames (also referred to as active video games or gamercizing) includes technology-driven physical activities in a gaming environment that require participants to become physically active to play the game.[72–74] Technology-based exercise devices allow for on-demand training, but the level of direct supervision is constrained by technical features (e.g., integration of sensors allowing for the assessment of physiological and/or kinematic data that can be used to provide feedback to the user). A clear allocation of technology-based exercise devices as either "synchronous" or "asynchronous" is somewhat difficult and depends on the interpretation of the terms since from a theoretical point of view, the criteria for both asynchronous interaction (i.e., on-demand training) and synchronous interaction (i.e., immediate feedback due to integrated sensors that can influence the course of the exergame) are fulfilled, although the latter strongly depends on the technological implementation.

### 2.4. *Screening of studies*

As shown in Fig. 2, 8258 studies were identified from the databases and 17 were retrieved from other sources. Eleven studies were retrieved from websites (e.g., platforms such as ResearchGate),[75–85] and 6 more were retrieved via a search for further publications by specific authors.[51,86–90]

Of the studies identified by the database searches, 98 were excluded after abstract and full-text screening because they did not meet at least 1 of the inclusion criteria.

- Participants: We excluded studies done in the wrong age range (e.g., children).[91–93]
- Intervention: Studies were excluded if no digital technologies were used to deliver the physical training intervention,[94–99] if there was only telephone contact,[100,101] if videoconference software was used for weekly monitoring calls but not to supervise exercise sessions,[102] if there was no home-based physical training intervention,[103–110] or if there was no physical training intervention.[111–117]
- Comparison: Pilot or feasibility studies without control groups were excluded.[118–123]
- Outcome(s): If there were no cognitive outcomes assessed, studies were excluded.[50,124–170]
- Study design: We excluded studies if they were not original articles but posters,[171–173] study protocols,[174–184] or reviews.[54,185,186]

Of the 17 studied identified by other sources, 14 were excluded based on the exclusion criteria.

- Intervention: Studies were excluded if no digital technologies were used to deliver the physical training intervention[78] or if there was no physical exercise intervention (only advice on physical activity).[90]
- Outcome(s): If there were no cognitive outcomes assessed, studies were excluded.[51,77,79–81,84,87–89]
- Study design: We excluded studies that were not original articles (e.g., study protocols).[82,83,86]

### 2.5. *Data extraction*

In the current systematic review, 2 authors (FH and PT) extracted the following data from relevant studies: (a) first author and year of publication; (b) population characteristics, including cognitive status, age, sex, and demographic information (i.e., body height, body mass, and body mass index); (c) exercise and training characteristics (e.g., type of physical

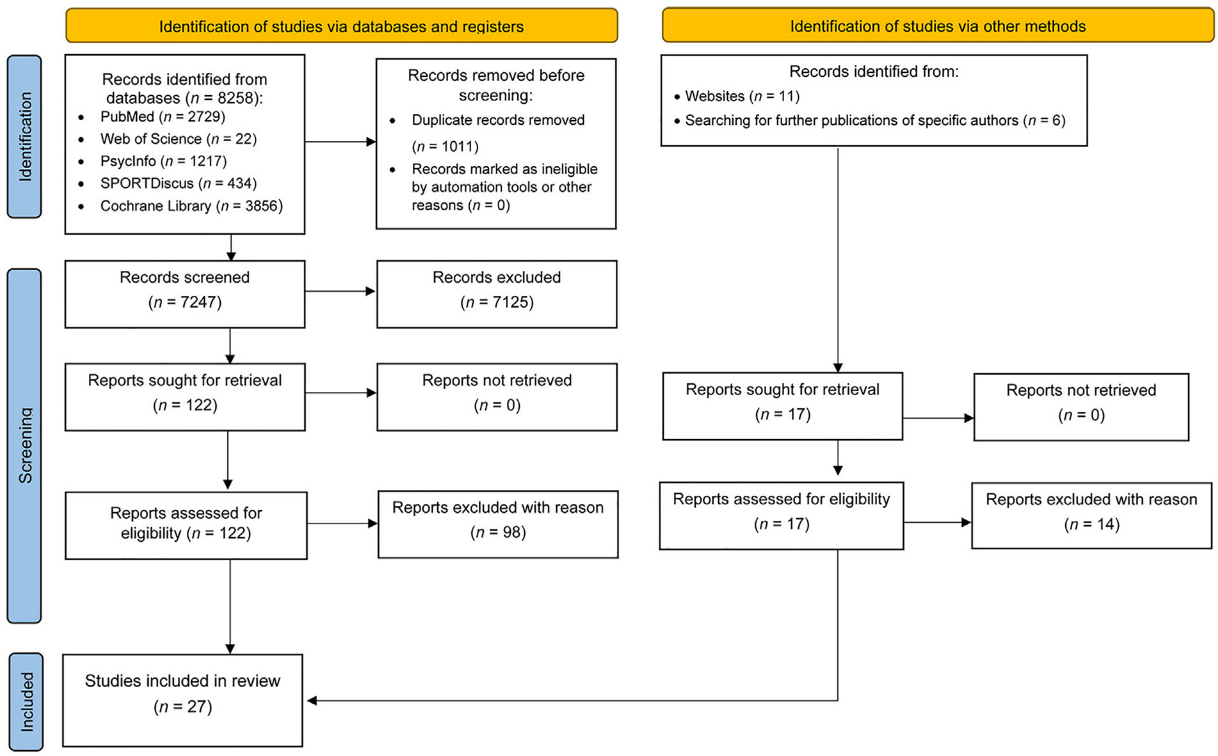


Fig. 2. Flow chart with information about the search, screening, and selection processes that led to the identification of relevant articles included in this systematic review. The figure was created using the template provided by Page et al.[62]

exercise, technical implementation, exercise intensity, exercise duration, training frequency, training density, training duration); (d) completion and attendance adherence or duration adherence, occurrence of adverse events; (e) characteristics of cognitive testing (e.g., tested cognitive domain, used cognitive tests); and (f) main findings related to cognitive performance. The definitions of specific terms (e.g., training density, attendance adherence) are provided in the notes of Supplementary Table 1. The extraction of exercise- and training-related characteristics was oriented on previous reviews.[187,188] If we were unable to identify and extract a specific piece of information from the original article or if any information of interest to the current systematic review was unclear in the original article, we contacted the authors 3 times via e-mail or social network (i.e., ResearchGate) to request further information.

### 2.6. *Risk of bias assessment*

The risk of bias assessment was conducted by 2 independent evaluators (FH and PT) using a modified version of the Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX scale).[189] As shown in Fig. 3, the TESTEX scale evaluates the methodological quality of a study by rating the risk of bias for distinct criteria.[189] In our modified version of the TESTEX scale, we rated the risk of bias as “low”, “high”, or “unclear” (Supplementary material-TESTEX scale), and we refrained from calculating a summary score due to the disadvantages of such an approach.[190] Any discrepancies in the ratings of the risk of bias were resolved by a discussion among the 2 evaluators (FH and PT) and/or consultation of the third author of the review (TG). The risk of bias assessment is summarized in Fig. 3.

## 3. Results

### 3.1. *Study and sample characteristics*

In this systematic review, we recognized 3 types of digital and home-based interventions: (a) digital databases, which were used in 7 studies;[191–197] (b) online classes, which were used in 4 studies;[76,85,198,199] and (c) technology-based exercise devices (e.g., exergames), which were used in 15 studies[200–214] (see the Methods section for definitions and Fig. 1 for an overview). One study used both a digital database and online classes to deliver the physical intervention.[75] The reviewed studies investigated the effects of digital and home-based physical training interventions on cognitive performance in younger adults,[76,85,198] adults with multiple sclerosis,[204,207] adults with Parkinson’s disease,[205,208,209,212] adults with cardiovascular diseases,[210] adults suffering from stroke,[213] healthy older adults,[192–197,200–203,211] older adults with mild cognitive impairment,[75,191,199] older adults with mild Alzheimer’s disease,[206] and older adults with dementia.[214] A more detailed overview of the general characteristics of the participants is provided in Supplementary Table 1.

All studies except for 1 study[198] were conducted in a parallel-group design and had either a passive control group,[76,85,191–194,200–204,209,211] an active control group,[75,195–197,199,206–208,212–214] or both.[193,210] Furthermore,

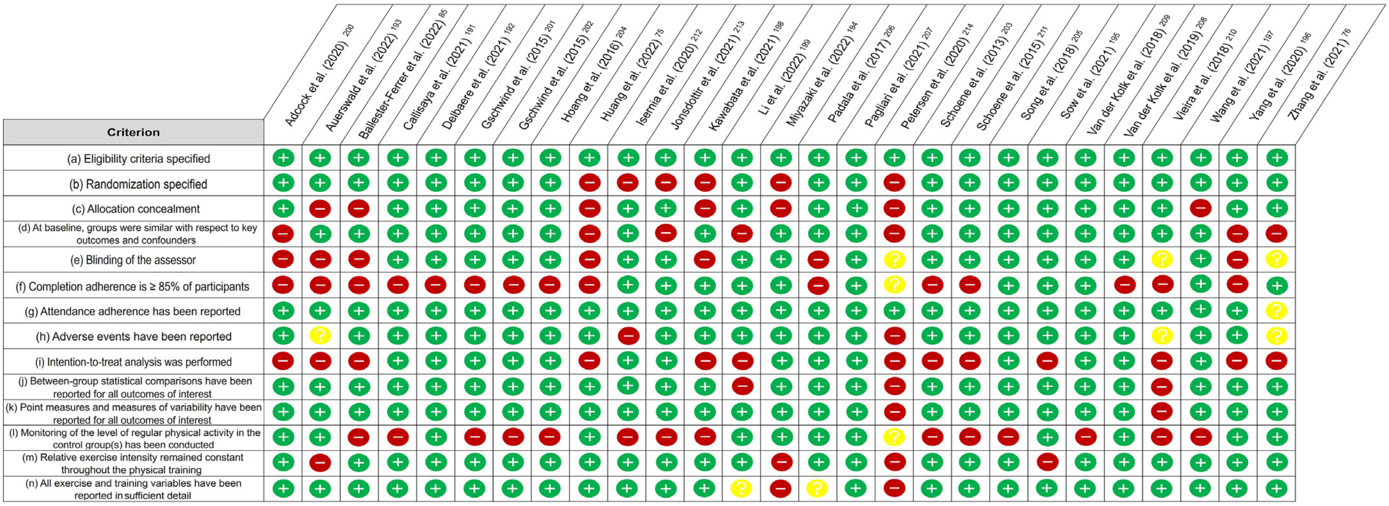


Fig. 3. Overview of the analysis of the risk of bias of the included studies. A "green plus" indicates a low risk of bias, a "yellow question mark" indicates an unclear risk of bias, and a "red minus" denotes a high risk of bias.

the majority of studies provided general supervision, meaning that physical exercise sessions were unsupervised but participants were regularly contacted by the healthcare professionals (i.e., the research team) and/or could contact the healthcare professional when they needed assistance.[85,191,192,194–197,200–205,207–213] All physical exercise sessions were directly supervised by a healthcare professional in 3 studies,[76,198,199] whereas the caregiver was asked to supervise physical exercise sessions in 1 study,[206] and participants' movements were tracked by a motion sensor in another study.[214] In the other studies, (a) regular in-person group meetings were conducted in which a physical exercise session[214] or a physical exercise session combined with a discussion of health education topics were performed;[193] (b) besides unsupervised home-based exercise sessions, regular online classes were conducted;[75] and (c) a 5-week-long supervised at-facility training was followed by 5 weeks of unsupervised home-based training.[85] In addition, only 4 out of the 27 studies were conducted as a group-based intervention,[76,85,198,199] whereas in the remaining studies participants either trained on their own,[191,192,194–197,200–213] conducted both group-based and individual training sessions during the training intervention period,[75] or performed some form of hybrid physical training intervention (i.e., consisting of center- and group-based exercise sessions as well as home-based individual exercise sessions).[193,214]

## 3.2. *Characteristics of the physical training interventions*

In the reviewed studies, the following exercise intensities were targeted with respect to the cardiorespiratory demand of the physical exercises: (a) light,[195] (b) light-to-moderate intensity,[75,199] (c) moderate intensity,[196,200] (d) moderate-to-vigorous intensity,[193,197,208] (e) vigorous intensity,[76,209,210] or all-out.[85] Some studies did not explicitly specify exercise intensity.[194,214] The exercise intensity was operationalized by using (modified) ratings of perceived exertion[75,76,85,191,192,197,199,210] or indices of heart rate.[75,85,196,208–210] Please note that we have rated the exercise intensity of the reviewed studies, if possible, according to the classification approach provided by the American College of Sports Medicine.[215] In this context, it was reported that the exercise intensity was (a) set to Level 11,[195] Levels 11–14,[75] or Levels 12–14[197] of the rate of perceived exertion (RPE) on a 6–20 RPE scale, (b) set to Levels 6–8 on a 0–10 RPE scale,[76] (c) on average, ~40% of heart rate reserve,[196] (d) set between 60%–70% of the maximum heart rate,[75] (e) set between 60%–80% of heart rate reserve and adapted during the intervention if needed,[209] (f) gradually increased from 50%–70% to 80% of heart rate reserve,[208] or (g) increased from 65% to 70% of heart rate reserve after 3 months.[210] In the remaining studies, a progression was achieved by increasing complexity (level of difficulty) based on the performance changes of participants.[191,192,199–206,211–214]

In addition, 2 studies reported that they offered for their participants to freely choose the duration of the exercise sessions (e.g., 15 min, 20 min, 25 min, or 30 min)[191,192] and stated that total exercise duration per week was progressively increased from 40 min (first 2 weeks of the intervention) to 120 min (from the 9th week of the intervention onwards).[191,192] Furthermore, 2 studies recommended that their participants perform 120 min of balance exercise and 60 min of resistance exercise[201,202] or 60 min of step exercises[211] per week. The resistance exercises included knee extension, knee flexion, hip abduction, calf raises, and toe raises. At the beginning of the intervention, 2–3 sets of 10–15 repetitions per resistance exercise (rest periods of 1 min) were performed, and progression was achieved by increasing the number of repetitions, the number of sets, or the load (e.g., via 1–3 kg ankle cuff weights).[201,202] In 1 study, participants performed 6 elastic band resistance exercises for the upper and lower limbs, consisting of 3 sets of 12–15 repetitions per exercise at a perceived exertion of 5–6 on the omnibus resistance exercise scale.[75] Another study provided a physical intervention oriented according to the recommendations of the World Health

Organization, including balance, flexibility, strength, and endurance exercises (e.g., 150 min with moderate-to-vigorous intensity endurance exercises per week in bouts of at least 10 min).[193] A detailed overview of the physical exercise variables and training variables is provided in Supplementary Table 1.

### 3.3. Main findings of the reviewed studies

In the following we will present the main findings of the reviewed studies according to the categories we have proposed to differentiate between different types of digital and home-based physical training interventions (Fig. 1).

#### 3.3.1. Digital databases

With respect to digital and home-based physical training interventions utilizing digital databases, no intervention-related changes in measures of cognitive performance were observed in healthy older adults[192,195,196] or in older adults with mild cognitive impairment.[191] In a study utilizing a DVD-based dancing intervention, the dancing group showed a superior performance concerning measures of global cognition and executive function as compared to the Nordic walking group and the passive control group after a 4-week-long intervention period.[194] Another study in healthy older adults observed that 12 weeks of a home-based multicomponent exercise intervention delivered via video can improve some measures of executive functioning but that the improvements in executive functioning were not as pronounced as in the active control group that performed lab-based exergame training.[197] Finally, a study reported improvements in executive functioning (i.e., reaction time in the Simon task) after a 10-week intervention in which healthy older participants received information via a website; however, no statistically significant differences were observed between the active and passive control groups.[193]

#### 3.3.2. Online classes

Concerning digital and home-based physical training interventions that used online classes, we found that (a) in younger adults, executive functions improved after a 2-week-long square-stepping intervention as compared to an active control condition in which stationary walking exercises were performed;[198] (b) in younger adults, global cognitive performance and episodic memory were enhanced after a 6-week-long bodyweight high-intensity training as compared to a passive control group;[76] (c) in younger adults, executive functioning (as measured by choice reaction time and interference tests) was improved after a 10-week-long intervention period, although there were no statistically significant differences between assessments at Week 5 (i.e., the end of facility-based training and start of home-based training) or Week 10 (i.e., the end of home-based training);[85] and (d) in older adults with mild cognitive impairment, 16 weeks of online Tai-chi training leads, at least on a descriptive level, to improvements in executive functions, working memory, and global cognitive performance, although no statistical comparisons were conducted.[199] Finally, in older adults with cognitive impairment no statistically significant changes in cognitive outcomes were noticed in an 8-week-long intervention utilizing both a digital database (via DVD) and online classes to deliver the training program.[75]

#### 3.3.3. Technology-based exercise devices

Regarding digital and home-based physical training interventions that employed technology-based exercise devices, the following intervention-related changes were noticed in the reviewed studies. Two studies in older adults reported an improvement in executive functions[200,210] and/or working memory[200] in response to an exergame intervention lasting 16 weeks[200] or 24 weeks.[210] One study in older adults reported greater improvements in executive functions after 16 weeks of step-mat training as compared to a training including balance and strength exercises or a passive control group.[202] Compared to a passive control group, 2 studies observed significant changes in performance measures of the choice stepping reaction task in older adults[203] and in older adults with multiple sclerosis[204] after 8 weeks or 12 weeks of exergaming, respectively. Comparable results were noticed when, after a 16-week exergaming intervention, older adults showed improvements in measures of motor performance (i.e., choice stepping reaction time, hand reaction time) and information processing performance as well as visuospatial performance when compared to a passive control group.[211]

In adults with multiple sclerosis, improvements in global cognitive performance, attentional performance, and memory performance were observed after a 6-week-long virtual reality training intervention comprising motor and cognitive exercises, although the between-group comparisons between intervention and control group were not statistically significant.[207] In comparison to a control group that received usual care, adults suffering from stroke showed better memory performance at the follow-up assessment conducted 12 weeks after completion of a 12-week-long intervention comprising motor and cognitive exercises.[213]

Seven studies using technology-based exercise devices did not observe statistically significant intervention-related changes in measures of cognitive performance in older adults,[201] older adults with mild Alzheimer's disease,[206] older adults with dementia,[214] or adults with Parkinson's disease.[205,208,209,212] A more detailed overview of the cognitive tests and intervention-related changes in measures of cognitive performance is provided in Supplementary Table 1.

### 3.4. Adverse events

In 14 studies no serious intervention-related adverse events were reported in younger healthy adults,[85,198] older adults,[195–197,201–203,211] adults with multiple sclerosis,[204] older adults with Parkinson's disease,[209] older adults with mild cognitive impairments or probable Alzheimer's disease,[75] older adults with mild Alzheimer's disease,[206] or older adults suffering from stroke.[213] In 6 studies minor intervention-related adverse events were noticed (i.e., new or aggravated symptoms of musculoskeletal pain, dizziness).[191,192,199,200,207,208] In addition, 1 non-injurious fall while performing the physical exercises was reported in a study with adults with mild cognitive impairment[191] and a study with adults with Parkinson's disease,[205] respectively. In 1 study investigating the effect of physical training and protein supplementation in older adults, 1 participant had temporary diarrhea due to the protein supplementation.[194] In 1 study adverse events were not assessed,[212] and in another the data has, at least so far, not been analyzed.[193] In 3 studies, there was no information provided (despite repeated requests) on whether or not intervention-related adverse events had occurred.[76,210,214]

### *3.5. Risk of bias*

A detailed overview of the risk of bias assessment is provided in Fig. 3. The majority of reviewed studies were rated as having a low risk of bias in the following categories: (a) eligibility criteria specified, (b) randomization specified, (c) allocation concealment specified, (d) reporting of group differences at baseline, (e) blinding of the assessor, (g) reporting of attendance adherence, (h) reporting of adverse events, (j) reporting of between-group statistical comparisons, (k) reporting of point measures and measures of variability for all outcomes of interest, (m) progressive increase of exercise intensity (complexity) to maintain the relative exercise intensity constant, and (n) the description of all exercise and training variables.

Regarding completion adherence (f), 15 of the reviewed studies were rated as having a high risk of bias since the completion adherence in those studies was lower than 85%. Furthermore, based on (l) the absence of appropriate monitoring of the level of regular physical activity in the control group, 14 studies were rated as having a high risk of bias in this category. In addition, 13 studies were rated as having a high risk of bias concerning (i) intention-to-treat analysis because those studies did not apply this statistical method to the analysis of their trial data (Fig. 3).

## 4. Discussion

The main aim of this systematic review was to summarize and discuss studies investigating the effects of digital and home-based physical training interventions on cognitive performance in the adult population. We identified 27 studies that met our inclusion criteria, and our systematic review of those studies provided rather mixed evidence for the effectiveness of digital and home-based physical training interventions on cognitive performance, suggesting that effectiveness is modulated by study-related, population-related, and intervention-related characteristics.

### *4.1. Exercise characteristics and main findings*

Overall, our analysis revealed a considerable degree of heterogeneity concerning the exercise and training characteristics and the effectiveness of the interventions. With respect to the latter, the evidence is relatively equivocal as only 15[76,85,193,194,197–200,202–204,207,210,211,213] of 27 studies reported intervention-related improvements in cognitive outcome parameters. However, a closer look at the included studies revealed a mixed effect on measures of cognitive performance in studies using digital databases, a positive effect in studies using online classes, and a mixed effect in studies using technology-based exercise devices (mainly exergames). Further analysis of studies using technology-based exercise devices indicated that effects on cognitive outcomes are influenced by study population. In particular, the available data suggests that technology-based exercise devices (i.e., step-based exergames with general supervision) are a promising instrument for improving cognitive performance in healthy older adults (i.e., 4 studies observed a positive effect[200,202,203,211] while 1 study found no such effect[201]), but they seem not to be effective in adults with Parkinson's disease.[205,208,209,212]

In general, our findings reinforce the ambiguity of evidence in this research field, with some systematic reviews and meta-analyses reporting improvements in cognitive performance after exergame interventions[216,217] and digital health interventions,[59] and others concluding that the available evidence is not sufficient to draw robust conclusions.[54,218] The lack of clear evidence concerning intervention-related cognitive performance changes may be caused by a multitude of factors known to influence the effectiveness and robustness of the effects of physical training on cognitive outcomes, such as study-related differences (e.g., sample size, adherence), population-related characteristics (e.g., age, sex, cognitive and health status), and intervention-related characteristics (e.g., exercise and training variables).[2,219,220] Physical training programs aiming to positively influence cognitive performance in older adults should be designed to either induce a re-activation of disused or damaged brain regions, or activate compensatory neural reserves.[221,222] Concerning healthy older adults, there is some evidence suggesting that combined simultaneous motor-cognitive training programs (including coordinative training) might lead to the greatest benefits with respect to neurocognitive outcomes.[2,223–225] In such intervention programs, the physical (motor) part should focus on aerobic activities performed at a moderate exercise intensity in an upright (standing) body position that requires weight bearing. Preferably, the integrated cognitive challenges would include multicomponent demands, including working memory and memory-specific training.[223] This assumption is at least partly supported by our findings, which show that in healthy older adults, home-based interventions utilizing online classes and technology-based exercise devices (i.e., step-based exergames) are especially likely to lead to cognitive performance improvements. In general, our observations are in line with the findings of a recent meta-analysis on digital health interventions, which reported that supervised and step-based exergame interventions induce the largest effects on measures of cognitive and physical performance in adults with mild cognitive impairment and dementia.[59] However, our assumptions concerning the effectiveness of different types of digital and home-based physical training interventions should be treated cautiously as (a) none of the reviewed studies directly compared different types of digital and home-based physical training interventions; (b) there are limited studies available concerning digital databases ($n = 7$)[191−197] and online classes ($n = 4$)[76,85,198,199] (note that 1 study used both a digital database and online classes[75]); and (c) there is relatively large heterogeneity among the included studies, especially with regard to study-related, population-related, and intervention-related characteristics (Supplementary Table 1). Therefore, with the research in its current state, it is not possible to draw more nuanced conclusions about the effectiveness of different types of digital and home-based interventions or to determine a dose−response relationship at this time.

This systematic review has contributed important insights into the effects of digital and home-based physical training interventions on cognitive performance, and it will be complemented by upcoming homed-based physical training studies planning to utilize digital databases[86,174,175] and online classes.[83,172] Nonetheless, additional high-quality studies will be required to obtain a comprehensive and nuanced understanding of the influence of digital and home-based physical training interventions on cognitive performance outcomes. In particular, more research is needed to address existing gaps in the literature. Future studies should aim to investigate possible dose−response relationships with respect to exercise and training variables[3,220,226,227] (although the optimal dose is yet to be determined[1,3,4,225] and the optimal operationalization of the dose is debated[226−228]); and directly compare the effectiveness of different types of digital and home-based physical training interventions on cognitive performance outcomes, as well as compare non-digital and digital home-based physical training interventions. The latter is a promising area for further research given the observation that in adults (regardless of age), digital and home-based physical interventions were found to be as effective as in-person interventions, at least with respect to certain physical and health-related outcomes (e.g., muscular strength or health responsibility).[77,81,129,132] In recognition of the fact that we don't fully understand the neurobiological mechanisms that drive changes in cognitive performance in response to physical training (neither in general[3,229,230] nor in digital and homed-based physical training interventions in particular), further studies are advised to consider multiple levels of analysis (i.e., Level 1: changes on molecular and cellular levels (e.g., levels of brain-derived neurotrophic factor); Level 2: functional and structural brain changes; and Level 3: socioemotional changes[229]) when they examine the effects of digital and home-based physical training interventions on cognitive performance. In this context, a mobile laboratory (e.g., in a bus) designed to bring the laboratory equipment to participants' homes could be a valuable option for assessing changes in parameters that are not easy to quantify remotely (e.g., functional brain activity recorded via functional near-infrared spectroscopy[231]).

### 4.2. Adverse events and risk of bias

Based on the reviewed studies, digital and home-based physical training interventions appear to be a safe alternative to center-based physical training program. In most of the reviewed studies, no serious intervention-related adverse events occurred. Our results are consistent with the findings of a recent systematic review and meta-analysis reporting that (home-based) physical training interventions can be considered safe.[232]

Regarding our risk of bias assessment, 2 major sources of bias emerged that might have confounded the findings of the reviewed studies to some extent and, thus, the findings of this systematic review (Fig. 3). Many of the reviewed studies were rated as having a high risk of bias with respect to completion adherence and monitoring the level of regular physical activity in the control group.

Completion adherence refers in a broad sense to the phenomenon of exercise motivation, which several theories[233−235] and determinants[236] have aimed at explaining. However, given that (a) the complex underlying mechanisms of exercise motivation, attendance adherence, and completion adherence are not fully understood and (b) exercise motivation, attendance adherence, and completion adherence are important prerequisites for cultivating the positive health effects of regular physical activity (e.g., in form of physical training), further research in this direction is necessary in order to develop effective strategies for increasing exercise motivation and, in turn, fostering attendance and completion adherence. It is worth mentioning that 3 out of 4 interventional studies using online classes with live remote contact between the trainer and trainees reported relatively high attendance and completion adherence rates.[76,198,199] This observation fits with the finding of a study in older adults that observed higher mean completion adherence and attendance adherence rates in the online class group (completion adherence: ~91% and attendance adherence: ~69%) compared to the digital database group (i.e., those who received the exercises via DVD; completion adherence: ~55% and attendance adherence: ~38%).[130] In younger adults, comparable findings have shown that attendance adherence to a 5 week-long digital and home-based physical intervention was slightly higher in the online class group (~93%) compared to groups that received the intervention program via digital databases (~86%) or written manuals sent to the smartphone of the participant (~74%).[237] Furthermore, the idea that (direct) supervision (e.g., providing feedback on proper exercise execution) is necessary to ensure appropriate adherence to physical training interventions, in general,[236] and to home-based physical training interventions, in particular,[185,238] is supported by the findings of other systematic reviews. However, given that none of the reviewed studies have directly compared different types of home-based and digital training interventions, no solid conclusions on whether measures of adherence vary as a function of the type of home-based and digital training interventions can be drawn. Thus, further research is necessary to explore this phenomenon and its influence on intervention-related changes of cognitive performance outcomes in more detail.

With respect to the monitoring of the level of regular physical activity in the control group, our risk of bias assessment reveals that more than one-half of the reviewed studies failed to appropriately account for this important confounder. Future studies are recommended to assess subjective markers of physical activity levels (e.g., via physical activity questionnaires or logs), objective markers of physical activity level (e.g., via physical activity trackers), or in the optimal case, both subjective and objective markers of physical activity levels during the intervention period in light of recent recommendations concerning the application of these methods.[239,240]

### 4.3. Strengths and limitations

A major strength of this review is its systematic summary of the current literature on a novel topic (namely, the effectiveness of digital and home-based physical training interventions on cognitive performance in adults) with adherence to established recommendations, ensuring a transparent and reliable identification of relevant research.[60−62] It is also worth noting that we not only focused on training-related changes in cognitive measures but also analyzed several influencing factors, such as study-related (e.g., sample size, adherence), population-related (e.g., age, sex, cognitive and health status), and intervention-related characteristics (e.g., exercise and training variables). Moreover, our comprehensive overview of the current state of the literature is complemented by the proposal of a theoretical framework for how digital and home-based physical training interventions can be classified. However, despite the several strengths of our systematic review, our findings should be interpreted in light of the following limitation. Only studies published in English were included, thus potentially relevant studies published in other languages were excluded. However, since no potentially eligible articles were excluded due to the language restriction during our screening, it is very unlikely this exclusion criterion substantially biased our results.

## 5. Conclusion and outlook

The evidence concerning the effectiveness of digital and home-based physical training interventions is rather mixed, as only 15 of the 27 reviewed studies reported a positive effect on measures of cognitive performance. However, a more detailed analysis suggests that home-based interventions using online classes and technology-based exercise devices (i.e., step-based exergames) are particularly promising approaches for improving cognitive performance in healthy older adults. Based on the limited number and considerable heterogeneity of the reviewed studies, more nuanced conclusions concerning a dose−response relationship cannot currently be drawn. Further high-quality studies are needed to verify the assumption that digital and home-based physical training interventions aimed at improving cognitive performance by providing purposefully developed intervention programs can be a valuable approach to fostering healthy cognitive aging.

## Authors' contributions

FH participated in conceptualization, methodology, validation, formal analysis, investigation, data curation, writing (original draft), visualization, and project administration; PT participated in conceptualization, methodology, validation, formal analysis, investigation, data curation, and writing (review and editing); TG and NK participated in conceptualization, writing (review and editing), and supervision; LZ, EDdB, and LB participated in writing (review and editing); NGM participated in writing (review and editing), resources, supervision, and project administration. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

## Competing interests

The authors declare that they have no competing interests.

## Supplementary materials

Supplementary materials associated with this article can be found in the online version at doi:10.1016/j.jshs.2023.01.004.

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