Digital Mindfulness Trainings and Cognitive Functions – A preregistered systematic review of neuropsychological findings

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Abstract

Traditional mindfulness interventions have been frequently reported to be effective in improving cognitive functions. In recent years, however, traditional programs are increasingly replaced by technology-enabled mindfulness interventions. The aim of the present systematic review (PROSPERO ID: CRD42021289480) was to evaluate the research evidence on their effects on cognitive functions. Empirical intervention studies in the realm of digital mindfulness trainings fulfilled the inclusion criteria, which led to 19 studies and 1,257 participants being included in this review among PubMed, Scopus, and Web of Knowledge. Results support previous assumptions on the potential of digital mindfulness trainings with the most robust effect on attention control, followed by executive regulation and memory, cognitive flexibility, and other cognitive functions. However, the number of studies that did not find significant changes at least equaled, if not exceeded, the number of studies that found increases. The heterogeneity of identified studies prompted us to discuss several aspects in order to help future development of digital applications.

1. Introduction

The future of mindfulness trainings is digital, and the future is now. This has been claimed by a recent opinion paper and is reflected by an overwhelming number of digital applications available (Mrazek, Mrazek, Cherolini, et al., 2019).

As the popularity of digital applications has increased (Mani et al., 2015; Plaza et al., 2013), so has the number of studies in the field. Most evidence comes from studies on health-related outcomes. Here, different reviews have proven the effects of digital trainings in improving stress, anxiety, depression, and well-being, summarized in numerous reviews (Fish et al., 2016; Mrazek, Mrazek, Cherolini, et al., 2019; Russell et al., 2018; Taylor et al., 2021). However, a systematic consideration of digital mindfulness training studies focusing on improvements in cognitive functions is still missing, which is the focus of the present review.

Mindfulness techniques are based on key elements of several Buddhist meditations – such as Vipassana (Gunaratana, 1993) and Zen (Kapleau, 1965) – but are now secularized and do not follow any philosophical or religious tradition (Kabat-Zinn, 1990). In recent years, different approaches, models, and theories have been developed, but all with a similar understanding: They describe mindfulness as a mode of purposeful, non-judgmental, and non-elaborative awareness to the present moment in which each thought, feeling, or physical sensation that arises is acknowledged and accepted as it is (Baer, 2003; A Chiesa & Malinowski, 2011; Grossman, 2011; Ivanovski & Malhi, 2007; Kabat-Zinn, 1990; Shapiro & Schwartz, 2000; Tang & Posner, 2013; Teasdale, 1999). As a kind of self-focused/self-regulated attention, mindfulness meditation addresses skills such as curiosity, openness, acceptance, emotion regulation, relaxation, as well as inhibition of elaborative processing through multiple body and mind-based techniques (Baer et al., 2006; Bishop et al., 2004; Brown & Ryan, 2003; Tang et al., 2017).

Traditional mindfulness programs are usually applied in a group or single session, on site, with a supervisor and thus limited in flexibility. Here, digital applications provide a possibility to meet the needs of our digital and fast-moving society by providing the possibility to practice mindfulness meditation regardless of time and place. In recent years, different kinds of digital mindfulness programs have been introduced, varying either according to the type of application or the content (Plaza et al., 2013; Zhu et al., 2017). Types of digital applications used in the context of mindfulness are app-based, web-based, text-/video-/audio-guided, remote, XR technology-based, or mixed, applied via smartphones, tablet-pcs, laptops, or desktop-pcs. The content used in digital mindfulness applications also varies largely (Plaza et al., 2013), from simple reminders to 10-week digital mindfulness-based stress reduction programs (Venkatesan et al., 2021).

As the field of digital mindfulness programs is still in its infancy – with no systematic review on their effects on cognitive functions so far – we do not focus on a specific type of digital mindfulness application or on a specific content. Rather, our aim is to provide a general overview and basis for future developments and studies.
In traditional mindfulness programs, the effect on cognitive functions have generally been proven in both clinical (Shapero et al., 2018) and non-clinical settings (Im et al., 2021). However, findings on specific cognitive functions in non-clinical samples are mixed (Cásedas et al., 2020; Alberto Chiesa et al., 2011; Lao et al., 2016; Whitfield et al., 2021). Within their meta-analysis on randomized controlled mindfulness studies, (Cásedas et al., 2020) identified small-to-medium effect sizes for executive control ($g = 0.34$), and inhibitory control ($g = 0.42$) but no significant effects on cognitive flexibility. For working memory, they report small-to-medium effects ($g = 0.42$). Here, findings are discussed to be driven indirectly by reductions in mind-wandering and distractions, as already proposed (Gallant, 2016). In contrast to Cásedas et al., (2020), Whitfield et al., (2021) did not identify improvements in inhibition, cognitive flexibility, and attention. Furthermore, the authors report smaller effect sizes in working memory ($g = 0.23$) and general executive functions ($g = 0.15$). With regard to the missing effects on attention, the authors argue with different processes involved in basic attention and attention regulation, which are more in common with executive functions (c.f., Petersen & Posner, 2012). A study by Im et al. (2021) – which focused on controlled mindfulness studies – also identified no training-related improvements in attention. Here, the authors argue that mindfulness exercises typically involve attention toward internal representations whereas tasks on attention, commonly used in studies, are designed to assess visual attention. In addition to the missing effects on attention, the authors also report no significant improvements in working memory but a small effect for executive function.

An earlier review on mindfulness-related effects on cognitive functions describes improvements in selective and executive attention in an early phase of practice and improvements in sustained attention and monitoring in later stages (Alberto Chiesa et al., 2011). Furthermore, the authors report mindfulness-related improvements in working memory and executive functions. No significant effect was identified in attention switching. However, within their review, the authors included both longitudinal as well as cross-sectional studies. With a focus on standardized programs and mindfulness training programs (e.g., mindfulness based cognitive therapy, mindfulness based stress reduction), Lao et al. (2016) identified improvements in working memory and cognitive flexibility but not in attention or executive function. From previous findings on traditional mindfulness meditation programs, it can be deduced that mindfulness meditation programs offer the potential to increase cognitive functions but effects should be considered specifically for each sub-component.

Therefore, we assume training-related effects of digital mindfulness applications on diverse cognitive functions. At the same time, inconsistencies in previous findings make it difficult to predict specific effects on subcomponents of cognitive functions. The increased flexibility of digital mindfulness application led us to assume an increasing likelihood of small dropout rates and lasting effects. In addition to proposed beneficial effects of increased flexibility, digital programs are faced by different challenges such as the level of support, degree of standardization, way of information presenting, audience diversity, maintaining engagement, as well as troubleshooting (Mrazek, Mrazek, Cherolini, et al., 2019). The present review aims to pick up these challenges and discusses potential solutions based on expected findings as well as findings from other fields of interest.

Objective

The purpose of this paper is to review and evaluate the evidence base on digital mindfulness trainings in the specific context of cognitive functions. This aim discriminates the present review from existing ones that addressed traditional mindfulness trainings (Cásedas et al., 2020; Alberto Chiesa et al., 2011), focused on health-related outcomes (Choo et al., 2018), or summarized characteristics of digital mindfulness trainings (Russell et al., 2018). Specific research questions address (1) the nature of digital mindfulness trainings, (2) the effectiveness of these trainings in improving cognitive functions (attention, memory, and executive functions), in (3) healthy adults, adolescents, and children. Furthermore, we are aiming to provide a model which summarizes the findings on different cognitive functions. The model might serve as basis for future studies in the field of digital mindfulness trainings.

2. Methods
The protocol for the present systematic review was pre-registered on PROSPERO International prospective register of systematic reviews (available from https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42021289480). PROSPERO adheres to the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2009).

2.1. Participants

Based on our aim to give a broad overview and the fact that the field is still in its infancy, we did not exclude studies with regard to participants’ age. Although the brain development and cognitive maturation change rapidly in children and adolescents, we did include these age groups. However, for further considerations we differentiate between samples of children/adolescents, adults, and older adults. We excluded studies with clinical samples, such as psychiatric (e.g., anxiety disorder) or neurological (e.g., dementia) patients.

2.2. Mindfulness-based programs/trainings

To be included in the present review, studies had to consider a digital mindfulness program/training. Here, it did not matter whether the application was app-based, web-based, text-/video-/audio-guided, remote, XR technology-based, or mixed. Furthermore, we included programs applied via smartphones, tablet-pcs, laptops, or desktop-pcs. However, studies with traditional in person programs (face-to-face) were excluded. Eligible programs/trainings needed to emphasize mindfulness as a primary component. Programs/trainings that used mindfulness components additionally to a cognitive trainings or other interventions were excluded. Studies on single unit mindfulness programs/trainings, programs/trainings that lasted several days/weeks as well as supporting mindfulness applications (e.g., reminder), were considered. All kinds of empirical studies were considered for inclusion in the review (case-studies, cohort studies, CTs, RCTs).

2.3. Cognitive function

To be included in the present review, studies had to consider at least one cognitive function or subdomain of attention, memory or executive functions. Both, computer-based and paper pencil tests, which provide objective and quantifiable behavioral data, such as reaction time or error rate, as well as neurobiological measures such as blood-oxygen-level-dependent (BOLD) signals and electroencephalography (EEG) were considered. Studies that quantified cognitive functions exclusively on self- or other-rated scores were not considered.

2.4. Additional criteria

Selected articles must be written in English, published in a peer-reviewed journal until November 2021, and report data from empirical studies.

2.5. Search Strategy and Study Selection

Two researchers independently searched the electronic databases PubMed, Scopus and Web of Knowledge for peer-reviewed articles published from Jan 1, 1985, to Nov 10, 2021. The search was conducted among abstracts and titles using the search terms (“Mindfulness meditation” OR Mindfulness OR Meditation OR Vipassana OR Zen) AND (Digital OR Mobile OR Computerized OR Computer OR Smartphone OR Online) AND (“Cognitive function” OR Cognition OR “Executive function” OR “Working memory” OR Updating OR Monitoring OR Memory OR Inhibition OR Inhibitory OR “Self-control” OR Attention OR Flexibility OR Shifting OR Switching). Search terms reflecting the kind of trainings (e.g., mindfulness, meditation), the kind of application (e.g., digital, mobile), and the cognitive functions (e.g., Attention, Inhibition) were combined within parentheses using a Boolean OR. These parenthesized entities were combined using a Boolean AND (Table 1). In addition, we searched the reference lists of retrieved articles. The identification and selection process, including abstract and full text review of identified studies, was performed by three trained research assistants under the supervision of the first author.

2.6. Study selection
Duplicate entries within the three databases were removed, initial screening was performed by checking titles, abstracts and study information (e.g., age and language) from the database. The remaining studies were subjected to full text review, to determine whether they met the eligibility criteria. To ensure objectivity and avoid mistakes in the study selection process each study was evaluated by two trained reviewers independently. Any discrepancies were discussed with the first author.

2.7. Data extraction

In accordance with the PRISMA guidelines (Moher et al., 2009), the following information was extracted: (1) author names and publication year; (2) study design; (3) sample characteristics (children/adolescents, adults, older); (4) sample size (total as well as for sub-groups); (5) mean ages and standard deviation; (6) cognitive functions considered; (7) detailed information about intervention and control conditions; (8) intervention type (e.g., app, remote); (9) duration; (10) number of sessions; (11) length of a session; (12) follow-up information; (13) Dropout. Data extraction was performed by the first author and checked by co-authors. When data were not available, we requested the missing data from the corresponding authors of the study.

Table 1 Search terms and their Boolean combination.

| mindfulness meditation" OR "mindfulness" OR "meditation" OR "Vipassana" OR "Zen" OR | AND | "digital" OR "mobile" OR "computerized" OR "computer" OR "smartphone" OR "online" OR | AND | "cognitive function" OR "cognition" OR "executive function" OR "working memory" OR "updating" OR "monitoring" OR "memory" OR "inhibition" OR "inhibitory" OR "self-control" OR "attention" OR "flexibility" OR "shifting" OR "switching" OR |

Effect interpretation and effect size calculations of interventions

Significant improvements in cognitive functions were indicated in cases where authors interpreted their results as significant improvements, for example based on significant F-tests, t-tests, or significant Z-statistics. We decided to not proceed to a meta-analysis since the studies we found were not homogenous enough.

3. Results

3.1. Search results

An initial search of databases resulted in 1,701 articles. Screening at title and abstract level and removal of duplicates resulted in an exclusion of 1,553 articles. This left 148 for full text screening, which further excluded 129, mainly due to studies not employing digital mindfulness programs/trainings or did not consider cognitive functions. Following, a total of
19 studies were included in this systematic review. The PRISMA flow diagram (Fig. 1) provides a comprehensive overview of the screening process and the reasons for exclusion.

3.2. Study characteristics

Within the studies included, digital mindfulness programs/trainings were investigated in children/adolescents (Mrazek, Mrazek, Reese, et al., 2019; Sethia et al., 2021), older people (Polsinelli et al., 2020; Tam et al., 2017; Wahbeh et al., 2016), as well as adults (Alimardani et al., 2020; Bhayee et al., 2016; Campillo et al., 2018; Eichel & Stahl, 2020; Krasich et al., 2018; Noone & Hogan, 2018; Rowland et al., 2019; Salehzadeh Niksirat et al., 2017; Schofield et al., 2015; Spadaro & Hunker, 2016; Walsh et al., 2019; Wang et al., 2021; Wolff & Beste, 2020; Ziegler et al., 2019). Participants in all studies reported no physical, neurological, and/or psychological disabilities. Eight studies investigated app-based mindfulness programs/trainings. Most apps include guided meditation with different practices like breathing, body-scan, focused attention meditation, or open monitoring. Some of those added information on mindfulness, provided feedback, or combined it with a mobile neurofeedback system. However, two studies differed significantly. The first study asked participants to perform slow finger movements on the screen and received visual feedback through a growing circle (Salehzadeh Niksirat et al., 2017). In the second study, a flame was presented that should be focused by the participants (Sethia et al., 2021). Web-based programs were the focus of six studies. Their flexible character in relation to the device used for application, distinguishes them from computer-based programs (two studies). Furthermore, one study each focused on a mindfulness program applied via an audio file (Schofield et al., 2015), a DVD program (Tam et al., 2017), or robot-assisted (Alimardani et al., 2020).

The duration of the programs ranged from one day (for a single session) to 56 days ($M = 23.58$ days, $SD = 18.38$) with a mean of 6.15 sessions ($SD = 16.36$). The length of each session varied from 6 minutes to 110 minutes ($M = 21.71$ minutes, $SD = 23.32$). Only two studies report a follow-up, of which one study did not consider cognitive functions in the follow-up (Spadaro & Hunker, 2016). The other study used a three weeks follow-up (Wang et al., 2021).

Drop-outs ranged from no dropouts to 82 in the intervention group ($M = 7.74$ numbers, $SD = 17.98$). In relation to the number of participants in the intervention groups ($M = 53.58$ numbers, $SD = 92.43$), this corresponds to approx. 15%. Only in one study it was not possible to assign dropouts to specific groups (Rowland et al., 2019). In eight studies no dropouts were reported, which were counted as no dropouts. Sixteen studies were controlled trials, of which 15 were randomized controlled trials. The remaining three studies were cohort studies. A more detailed description of the studies can be found in Table 1. Furthermore, in the appendix we provide an overview of the different digital mindfulness trainings investigated in the studies.

Table 1 Overview of All Included Digital Mindfulness Studies and Their Effects on Cognitive Functions.
<table>
<thead>
<tr>
<th>Study</th>
<th>Study design</th>
<th>Subjects</th>
<th>Number of subjects</th>
<th>Type of control</th>
<th>Measures</th>
<th>Main findings for cognitive functions</th>
<th>Dropout</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>App-based</strong></td>
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<tr>
<td>Niksirat et al. (2017)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 18 (M&lt;sub&gt;age&lt;/sub&gt; = 27 years, SD = 4.3)</td>
<td>Different mindfulness app [Headspace]</td>
<td>Attention Network Test</td>
<td>Alerting effect ↔ Orienting effect ↔ Conflict effect ↑</td>
<td>N = 0</td>
</tr>
<tr>
<td>Noone et al. (2018)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 91 (M&lt;sub&gt;age&lt;/sub&gt; = 20.92 years, SD = 4.39)</td>
<td>Sham meditation</td>
<td>Sternberg working memory task</td>
<td>Working memory ↔</td>
<td>N = 20</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Intervention n = 43 (M&lt;sub&gt;age&lt;/sub&gt; = 20.77 years, SD = 4.11)</td>
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<td>Intervention n = 7</td>
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<td></td>
<td>Control: n = 48 (M&lt;sub&gt;age&lt;/sub&gt; = 21.06 years, SD = 4.67)</td>
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<td></td>
<td>Control: n = 13</td>
</tr>
<tr>
<td>Bhayee et al. (2016)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 26</td>
<td>Online math training</td>
<td>Stroop task (RT/IC)</td>
<td>Inhibition ↑ Sustained attention ↔ Working memory ↔</td>
<td>N = 17</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Intervention n = 13 (M&lt;sub&gt;age&lt;/sub&gt; = 33.3 years, SD = 4.7)</td>
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<td>Intervention n = 7</td>
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<td></td>
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<td></td>
<td>Control n = 13 (M&lt;sub&gt;age&lt;/sub&gt; = 32.0 years, SD = 4.9)</td>
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<td></td>
<td>Control n = 10</td>
</tr>
<tr>
<td>Ziegler et al. (2019)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 42 (Age = 18–35 years)</td>
<td>Three placebo control apps performed in equal parts: 1/3 Language learning App, 1/3 Tai Chi App, 1/3 Logic Games App</td>
<td>EEG (Frontal Midline Theta &amp; P3b) Test of Variables of Attention Filter Task Change Localization Task</td>
<td>Frontal theta inter-trial coherence ↑ Parietal P3b latency ↑ Sustained attention ↑ Working memory ↑</td>
<td>N = 17</td>
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<td></td>
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<td></td>
<td>Intervention n = 22</td>
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<td>Intervention n = 10</td>
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<td></td>
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<td>Control n = 20</td>
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<td>Control n = 7</td>
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</tbody>
</table>

*Note. ↑ = significant increase; ↘ = different tests on the same cognitive function showed a significant increase as well as no significant differences; ↔ = nonsignificant difference, based on the authors’ interpretations*
<table>
<thead>
<tr>
<th>Study</th>
<th>Study design</th>
<th>Subjects</th>
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<th>Measures</th>
<th>Main findings for cognitive functions</th>
<th>Dropout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walsh et al. (2019)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 86</td>
<td>Cognitive training app</td>
<td>Centre for Research on Safe Driving-Attention Network</td>
<td>Alerting effect ↔ Orienting effect ↔ Conflict effect †</td>
<td>N = 22</td>
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<td></td>
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<td></td>
<td>Intervention n = 45 (M&lt;sub&gt;age&lt;/sub&gt; = 20.24 years, SD = 2.63)</td>
<td>Control n = 41 (M&lt;sub&gt;age&lt;/sub&gt; = 19.78 years, SD = 2.43)</td>
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<tr>
<td>Eichel &amp; Stahl (2020)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 42 (M&lt;sub&gt;age&lt;/sub&gt; = 24.3 years, SD = 5.5)</td>
<td>Progressive muscle relaxation (Audio)</td>
<td>Experimental paradigm (Error-processing) EEG-ERP</td>
<td>Error-rate † Ne/ERN ↔ Pe/ERN ↔</td>
<td>N = 3</td>
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<td></td>
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<td></td>
<td>Intervention n = 22</td>
<td>Control n = 20</td>
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<tr>
<td>Wolff &amp; Beste (2020)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 19 (M&lt;sub&gt;age&lt;/sub&gt; = 26.21 years, SD = 4.90)</td>
<td>No intervention</td>
<td>Task-switching paradigm EEG-ERPs (N1, N2, P1, P3)</td>
<td>Attention switching ↓</td>
<td>Ø</td>
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<td></td>
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<td></td>
<td>Intervention n = 10</td>
<td>Control n = 9</td>
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<tr>
<td>Sethia et al. (2021)</td>
<td>Cohort</td>
<td>Children</td>
<td>N = 11 (Age = 10–15 years)</td>
<td>Ø</td>
<td>Letter cancellation test</td>
<td>Sustained attention †</td>
<td>Ø</td>
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**Web-based**

*Note.* † = significant increase; ↗ = different tests on the same cognitive function showed a significant increase as well as no significant differences; ↔ = nonsignificant difference, based on the authors' interpretations
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<th>Dropout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krasich et al. (2018)</td>
<td>RCT</td>
<td>Adults</td>
<td>N = 83 ($M_{age}$ = 19 years, $SD = 1.10$)</td>
<td>Control I: Relaxation exercise + sitting in silence</td>
<td>Deliberate and spontaneous mind wandering</td>
<td>Mind-wandering↔</td>
<td>N = 11</td>
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<tr>
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<td>Intervention $n = 24$</td>
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<td>Intervention $n = 6$</td>
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<td></td>
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<td>Control I $n = 29$</td>
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<td>Control I $n = 4$</td>
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<td>Control II $n = 30$</td>
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<td>Control II $n = 1$</td>
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<td></td>
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<td>Control II: Waitlist</td>
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<tr>
<td>Wang et al. (2021)</td>
<td>RCT</td>
<td>Adults</td>
<td>$N = 32$ ($M_{age} = 30.06$ years, $SD = 11.27$)</td>
<td>Wait-list control condition (conducted the same intervention 6 weeks later and are considered in the findings)</td>
<td>Time estimation continuous performance Trail Making Test Verbal interference Go-NoGo Maze Choice reaction time Memory recall and recognition Corsi Block.tapping Digit span Emotion recognition</td>
<td>Attention ↔ Attention switching ↑ Cognitive flexibility ↔ Inhibition ↔ Executive functions ↑ Information processing ↔ Memory (verbal learning) ↑ Working memory ↑ Social cognition ↑</td>
<td>N = 8</td>
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<td></td>
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<td>Intervention: $n = 17$</td>
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<td></td>
<td>Intervention $n = 4$</td>
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<td></td>
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<td>Control: $n = 15$</td>
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<td>Control $n = 4$</td>
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</thead>
<tbody>
<tr>
<td>Polsinelli et al. (2020)</td>
<td>RCT</td>
<td>Older</td>
<td>$N = 50$ ($M_{age} = 75.70$ years, $SD = 5.70$)</td>
<td>Mind-wandering training</td>
<td>Keep Track task, Simon Task, Attentional Blink paradigm, Emotional Interference Task</td>
<td>Working memory ↔ Inhibition ↔ Visual attention↗</td>
<td>$N = 7$</td>
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<tr>
<td></td>
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<td></td>
<td>Intervention $n = 27$</td>
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<td>Intervention $n = 2$</td>
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<td>Control $n = 23$</td>
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<td>Control $n = 5$</td>
</tr>
<tr>
<td>Wahbeh et al. (2016)</td>
<td>RCT</td>
<td>Older</td>
<td>$N = 16$ ($M_{age} = 76.20$ years, $SD = 7.40$)</td>
<td>General health information video + podcasts</td>
<td>Auditory-Verbal Learning Test, Controlled Oral Word Association, Flanker Task, Letter-Number Sequencing, Simple Reaction-Time Task</td>
<td>Memory (verbal learning) ↔ Verbal fluency ↔ Inhibition ↔ Working memory ↔ Attention ↔</td>
<td>$N = 5$ (incl. 1 before randomization)</td>
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<td>Intervention $n = 3$</td>
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<td>Control $n = 8$</td>
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<td>Control $n = 1$</td>
</tr>
<tr>
<td>Spadaro &amp; Hunker (2016)</td>
<td>Cohort</td>
<td>Adults</td>
<td>$N = 26$ (Age = 25–60 years)</td>
<td>$\emptyset$</td>
<td>Attention Network Test</td>
<td>Alerting ↔ Orienting ↔ Conflict effect</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>Mrazek et al. (2019)</td>
<td>Cohort</td>
<td>Adolescent</td>
<td>$N = 190$ (9th–12th grade students)</td>
<td>$\emptyset$</td>
<td>Emotion Regulation Questionnaire for Children and Adolescents</td>
<td>Emotion regulation ↑</td>
<td>$N = 82$</td>
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</table>

**Note.** ↑ = significant increase; ↗ = different tests on the same cognitive function showed a significant increase as well as no significant differences; ↔ = nonsignificant difference, based on the authors’ interpretations
<table>
<thead>
<tr>
<th>Study design</th>
<th>Study design</th>
<th>Subjects</th>
<th>Number of subjects</th>
<th>Type of control</th>
<th>Measures</th>
<th>Main findings for cognitive functions</th>
<th>Dropout</th>
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<td>Rowland et al. (2019)</td>
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<td>Adults</td>
<td>$N = 137$ ((M_{\text{age}} = 23.08, SD = 5.04))</td>
<td>Wait-list control condition</td>
<td>State Self-Control Capacity Scale</td>
<td>State self-control ↑ Habitual self-control ↔</td>
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<td>Control $n = 69$</td>
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<tr>
<td>Campillo et al. (2018)</td>
<td>RCT</td>
<td>Adults</td>
<td>$N = 50$ ((M_{\text{age}} = 32.60 \text{ years}, SD = 11.37))</td>
<td>Audio track divided into the same categories as the Intervention group (visual)</td>
<td>Trail Making Test Digit Span</td>
<td>Attention switching ↑ Working memory ↑</td>
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<td>Schofield et al. (2015)</td>
<td>RCT</td>
<td>Adults</td>
<td>$N = 794$ ((M_{\text{age}} = 19.64 \text{ years}, SD = 3.24))</td>
<td>Audio informative on raisins</td>
<td>Inattentional Blindness Task</td>
<td>Visual Attention ↑</td>
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**Note.** ↑ = significant increase; ↗ = different tests on the same cognitive function showed a significant increase as well as no significant differences; ↔ = nonsignificant difference, based on the authors’ interpretations
### 3.3. Effects of digital mindfulness programs on cognitive functions

In the following, findings on the effects of digital mindfulness programs on cognitive functions are described within seven categories. The categories are based on the four key components that have been proposed in the most common mindfulness models (Hölzel et al., 2011; Malinowski, 2013; Tang et al., 2015). In addition, we included the categories ‘memory’ as well as ‘other cognitive functions’. The latter includes those functions that could not be assigned directly to one of the five categories of attention control, executive regulation, self-awareness, cognitive flexibility, or memory, but were subject of research in the studies considered. Figure 2 provides an overview of the number of studies as well as pooled sample sizes for significant and non-significant findings of each category. Within the category ‘neurophysiology’ we describe findings from studies included that focus on the underlying mechanisms.

#### 3.3.1. Attention control

Attention was most frequently the focus of interest, with eleven of the 19 studies including at least one variable related to attention. Based on the manageable number of studies in the present review, we decided to summarize different components of attention in one chapter but consider them in a dedicated manner. Sustained attention was subject of investigation within three studies. Two reported intervention-related improvements (Sethia et al., 2021; Ziegler et al., 2019), whereas one identified no effects (Bhayee et al., 2016). All three studies used app-based mindfulness applications. However, their content differed largely. Positive effects on visual attention in terms of attentional blink and inattentual blindness were reported in two studies (Polsinelli et al., 2020; Schofield et al., 2015). In (Polsinelli et al., 2020) the authors...
used different parameters to investigate the attentional blink, showing partially significant improvements. Here, participants completed 42 sessions mindfulness program which based on a modified script from Jon Kabat-Zinn’s guided practice for Mindfulness Based Stress Reduction (Kabat-Zinn, 1990). In contrast, Schofield et al. (2015) used a single session with an audio guide on mindfully attending. Two studies included the Attention Network Test (Salehzadeh Niksirat et al., 2017; Spadaro & Hunker, 2016). The test focuses on the three attentional networks alerting, orienting, and executive control/conflict monitoring. A modified version of the test was used by (Walsh et al., 2019). After eight weeks of an asynchronous, web-based mindfulness intervention based on MBSR (Spadaro & Hunker, 2016) did not produce significant changes in any of the three components. However, Salehzadeh Niksirat et al. (2017) and Walsh et al. (2019) applied a mindfulness app and report changes within the third attentional network (executive control) but not in alerting or orienting. Three studies used general/indirect measures of attention that cannot be assigned to specific components (Krasich et al., 2018; Wahbeh et al., 2016; Wang et al., 2021). All studies applied web-based programs with two studies programs similar to traditional programs and one with a single-session of one minute guided relaxation followed by a five minute guided mindfulness exercise (Krasich et al., 2018). However, neither report an improvement in attention.

### 3.3.2. Executive regulation

Six studies report findings on inhibition, self-control, and emotion regulation. Furthermore, one study considered general executive functions by using the Maze task where findings cannot be assigned to a specific function (Wang et al., 2021). Here, the authors identified improvements following six weekly web-based mindfulness sessions, as well as in the follow-up. Four studies focused on inhibition (Bhayee et al., 2016; Polsinelli et al., 2020; Tam et al., 2017; Wahbeh et al., 2016; Wang et al., 2021). However, solely the app-based program showed significant improvements (Bhayee et al., 2016). Of the four studies that found no effect, three used a web-based application and one applied a DVD program (Tam et al., 2017). In addition to the missing effect on inhibition, Polsinelli et al. (2020) could not identify any training-related improvement in emotion regulation. In contrast, Mrazek, Mrazek, Reese, et al. (2019) report significant improvements in the Emotion Regulation Questionnaire for Children and Adolescents. However, study designs, samples, and interventions differ largely between the two studies (Mrazek, Mrazek, Reese, et al., 2019; Polsinelli et al., 2020). Intervention-related effects on self-control were investigated in one study (Rowland et al., 2019). Here, the authors report improvements in state self-control but not in habitual self-control, following five sessions of a computer-based breathing meditation.

### 3.3.3. Self-awareness

None of the studies included any parameter of self-awareness.

### 3.3.4. Cognitive flexibility

Four studies investigated training-related differences in cognitive flexibility/switching attention. Three studies used the Trail Making Test to quantify switching attention with two having identified improvements (Campillo et al., 2018; Wang et al., 2021) and one with no effect (Tam et al., 2017).

Wang et al. (2021) identified positive results on switching attention, which also showed up in the follow up but no improvements in the stroop task, which was used to further quantify cognitive flexibility. The fourth study applied a single session app-based focused attention meditation (Wolff & Beste, 2020). Here, the authors identified a significant negative effect on attention switching.

### 3.3.5. Memory

All of the eight studies that investigated memory-related parameters included measures on working memory. Three out of the eight studies addressed further memory parameters. Here, two focused on verbal learning (Wahbeh et al., 2016; Wang et al., 2021) and one on episodic memory (Tam et al., 2017). Wang et al. (2021) identified improvements on verbal learning following a six-week intervention which persisted in the 3-weeks follow-up. In contrast, (Wahbeh et al., 2016) did not find significant intervention-related effects on verbal learning. Findings on episodic memory show significant improvements.
related to the intervention (Tam et al., 2017). In working memory, five studies identified no training-related effect (Bhayee et al., 2016; Noone & Hogan, 2018; Polsinelli et al., 2020; Tam et al., 2017; Wahbeh et al., 2016), whereas three did. However, those who did find significant improvements clearly differ in their kind and content of training as well as the study design. The three studies include one app-based (Ziegler et al., 2019), one web-based (Wang et al., 2021), and one computer-based program (Campillo et al., 2018).

### 3.3.6. Other cognitive functions

Four studies included parameters that could not be assigned to either of the five categories. Verbal fluency was addressed in two studies but neither could identify significant intervention-related effects (Tam et al., 2017; Wahbeh et al., 2016). Information processing and social cognition were considered by (Wang et al., 2021). Here, improvements were identified in social cognition but not in information processing after six weeks of training. Furthermore, improvements in social cognition persisted in the three weeks follow-up. Improvements in error-processing related to a four weeks app-based program with more than 56 sessions of guided and silent meditation were reported by (Eichel & Stahl, 2020).

### 3.3.7. Neurophysiology

In addition to behavioral parameters, neurophysiological measures were used in four studies. All used EEG to quantify either changes in event-related potentials (Eichel & Stahl, 2020; Wolff & Beste, 2020; Ziegler et al., 2019) or frequency bands (Alimardani et al., 2020; Ziegler et al., 2019). In event-related potentials, significant effects are limited (Ziegler et al., 2019). Within their Closed-loop app-based mindfulness program, participants performed short lessons on mindfulness breathing for six weeks. Individual sessions became longer with increasing experience. Along with positive changes in parietal P3b latency, the authors identified improvements in frontal theta inter-trial coherence (Ziegler et al., 2019). Mixed findings on frequency bands were reported by Alimardani et al. (2020). After a single six minutes robot-assisted breathing mindfulness meditation intervention, the authors reported positive changes in right-sided activity in the occipital gamma band. However, no effects were identified in fronto-central activations in alpha and theta frequency bands (Alimardani et al., 2020).

### 4. Discussion

Within the present review we focused on the effectiveness of technology-enabled mindfulness interventions on cognitive functioning. We identified eight app-based, six web-based, two computer-based, one mobile audio, one robot-assisted, and one DVD program. Results of this review support previous assumptions on the potential of mindfulness meditation to improve cognitive functions and alter neural mechanisms (Chiesa & Malinowski, 2011; Eberth & Sedlmeier, 2012; Jha et al., 2019; Tang et al., 2015). Specifically, the results show that digital mindfulness interventions have the most robust effect on attention control, followed by executive regulation and memory, cognitive flexibility, and other cognitive functions. There was no study that investigated the effects on self-awareness. Notably, the number of studies that did not find significant changes at least equaled, if not exceeded, the number of studies that found increases. That is, the evidence base in this review is rather heterogeneous with a potential for technology-enabled mindfulness interventions that is possibly not more than an incidental finding. There are several reasons that could provide an explanation for these results and will be discussed in the following in order to help future development of digital applications.

#### Structure and content of training

Studies included in the present review show a large variance with regard to structure and content of digital mindfulness trainings. Structure-wise, the duration of the trainings ranges from one day to eight weeks. Likewise, the length of single sessions ranges from 5 minutes to 110 minutes. But most importantly, also the content of the trainings shows a considerable diversity. Furthermore, and in contrast to classical mindfulness programs (e.g., IBMT, MBSR) that follow a given structure (Kabat-Zinn, 1990; Tang et al., 2007), none of the trainings being considered in this review have been tested in more than one study. Here, the content ranges from well-established body scans (Noone & Hogan, 2018) to a candle gaze concentration technique (Sethia et al., 2021) as well as an application asking for slow, continuous finger movements on the
screen with visual feedback (Salehzadeh Niksirat et al., 2017). Furthermore, digital mindfulness trainings need to be considered critically, regarding the basic idea of mindfulness meditation. That is, the key aspects of mindfulness meditation encounter 1) paying attention in the present moment, 2) on purpose, and 3) non-judgmentally. However, digital mindfulness interventions might be especially susceptible to violations of these key aspects since there does not yet exist a standardized digital mindfulness protocol. This leaves much room for research groups to come up with their specific training ideas. For example, within the closed-loop approach introduced by Ziegler et al. (2019), the user is asked to evaluate their level of mind-wandering that is used to adjust their training conditions. This is not congruent with the basic idea of a non-judgmental acceptance of intrusive thoughts and rather motivates the users to suppress their thoughts. In this regard Alberts et al. (2012) showed that accepting participants outperformed those who suppressed their thoughts in a subsequent self-control task. These findings support the importance of a proper way of instructing participants. A similar criticism applies to the level of gamification implemented in digital mindfulness applications. Learning curves, current streaks, and the displaying of achievement all provoke a feeling of competition and underline the importance of success. These feelings, however, are again in contrast with a non-judgmental attitude towards feelings and thoughts. Until now, web-based programs encompass the highest degree of the basic idea of mindfulness meditation and still correspond to the aspects of mobile applications.

Level of spatial flexibility

In technology-enabled mindfulness interventions, spatial flexibility is frequently described as major advantage (Asuncion et al., 2010; Fichten et al., 2000; Laurie & Blandford, 2016; Mrazek, Mrazek, Cherolini, et al., 2019). However, spatial flexibility increases the risk that people perform mobile trainings while being around with others or during other cognitively demanding activities, leading to distractions and impairs mindfulness meditation practice (Lawrence et al., 2015). From basic research we know that even quiet music can be distracting which increases by adding voices or disturbing noises (Hygge et al., 2003; Perham et al., 2016; Shih et al., 2012). Therefore, each mindfulness meditation session generally starts with the instruction to choose a place without any disturbance. This is of specific relevance in app-based applications as they can be used at any time and any place. In contrast, web-based programs, which simply transfer traditional programs in an online setting, offer the possibility to provide a certain level of spatial flexibility but with a certain amount of being controlled by a ‘real’ teacher, in a group setting, at fixed appointments, which will be discussed in the following (Greenberg et al., 2019).

Level of guidance & control

A higher level of spatial flexibility is usually associated with a reduced level of guidance and control and vice versa. This is particularly evident in app-based programs where the level of guidance is limited to standardized instructions and the level of control is solely ensured by system internal feedback. In web-/computer-based programs both the level of guidance as well as the level of control largely differ between individual applications. Here, the key factor could constitute the involvement of a real supervisor who is giving recurrent feedback. According to self-determination theory, the need to feel competent is one underpinning of human motivation and learning success (Ryan & Deci, 2000). In order to gain a feeling of mastery and that one is capable and effective, receiving constructive feedback is essential (Ryan & Deci, 2020). However, within the considered web-/computer-based programs solely one program used a video conference system with a real person introducing the mindfulness training (Wang et al., 2021). In order to increase flexibility while still allowing a higher level of guidance and control Krasich et al. (2018) introduced an intelligent tutoring system with which the participants interacted. However, most of the web-/computer-based programs did not involve any kind of supervision and solely provided information by the system (Campillo et al., 2018; Polsinelli et al., 2020; Rowland et al., 2019; Spadaro & Hunker, 2016). A mixed method with sessions onsite with a real supervisor and those without was described by (Wahbeh et al., 2016). In addition to the web-/computer-based programs, mobile audio applications as well as DVD programs provide no control as well as a limited level of instructions (the same standardized information for all users) (Schofield et al., 2015; Tam et al., 2017). Combining web-based and in-person delivery may be a solution. In a pilot longitudinal randomized study,
we applied both web-based and in-person classes of 10-session of IBMT (5 sessions each) in healthy adults and found significant improvements in emotion regulation and decreases in perceived stress and anxiety with large effect size (Cohen's dz > 1.12 in average). Moreover, non-invasive 3T proton magnetic resonance spectroscopy also detected significant brain metabolism changes in the anterior cingulate cortex, consistent with our previous RCT results in the functional and structural changes in the same area. These results may suggest a promising way to deliver mindfulness meditation programs (Tang & Tang, 2020).

So far, reviews on traditional mindfulness programs most frequently criticized the lack of scientific rigor, the lack of high quality randomized controlled studies as well as the inclusion of non-specific practices, as well as the frequent use of self-report instruments as measures of improvements (Alberto Chiesa et al., 2011; Goldberg et al., 2017; McKeering & Hwang, 2019). In contrast, almost 80% of included studies (15 of 19 studies) in the present review were designed as randomized controlled trials with no case study being identified. However, the RCTs largely varied in their sample sizes from \( N = 13 \) (Wolff & Beste, 2020) to \( N = 734 \) (Schofield et al., 2015) with both active control group and no intervention. However, the main limitation of the studies considered in the present review relates to the large variety of programs. Here, future studies should increasingly aim at developing standardized digital mindfulness programs which should be tested in different settings (e.g., different samples). The present review might provide a basis as well as describes key aspects that should be considered in conducting future programs and studies in the field of digital mindfulness applications. In addition, existing studies in the field still lack the consideration of long-term effects, which should be also the focus of future research.

5. Conclusion

In summary, this review focuses on mindfulness meditation effects on cognitive functions and alterations in neural mechanisms through mobile applications. We highlight the previous findings and discuss advantages as well as potential risks of the different types of digital applications. To date, findings on the effects of technology-enabled mindfulness trainings on cognitive functions are mixed. However, as the mobile or app-based programs will become inevitable in the present future, how to design an effective application and optimize the application to improve mindfulness meditation effectiveness would be a priority for translational research. Given that humans are social animals, social support and group interaction in traditional approaches should be included in the design of digital applications to reduce the disadvantages of mobile delivery and maximize benefits. In addition to the online disseminating mindfulness meditation, online assessment of its impact is also crucial and requires the solution of some key methodological challenges such as standardizing training across sites and individual differences.

Declarations

Ethics approval and consent to participate

Permission to conduct this systematic review was obtained from the Ethics Committee of the Department of Computer Science and Applied Cognitive Science, Faculty of Engineering. All information sources used in this study had been published before and were therefore in the public domain, but general ethical principles were applied.

Consent for publication

Not applicable

Availability of data and materials

The study is a systematic review and the information that formed the findings was extracted from the articles listed in Table 1.

Competing interest
The authors proclaim that there is no potential conflicts of interests to the researcher, authorship, and/or publication of this article.

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**Authors’ contributions**

M.L. and Y.Y.T came up with the idea; M.L., Y.Y.T., A.B., and M.B. designed the review; M.L. and A.B. screened and analyzed the data; M.B. supervised the screening process; Y.Y.T contributed in supervision of the review. All authors wrote and approved the manuscript.

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**References**


**Figures**

**Figure 1**

*Flow-chart of identified articles and exclusions*
**Figure 2**

*Effects of Digital Mindfulness Trainings on Cognitive Functions.*

*Note.* Figure is based on components of the most common mindfulness models (blue boxes) (Hölzel et al., 2011; Malinowski, 2013; Tang et al., 2015) and complemented by memory and ‘other cognitive functions’ (green boxes).

**Supplementary Files**

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- Appendix.docx