Augmented Visual Feedback-Aided Interventions for Motor Rehabilitation in Parkinson's Disease: A Systematic Review

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Abstract

Purpose: A systematic review was performed to (1) evaluate the effectiveness of augmented visual feedback-based treatments for motor rehabilitation in Parkinson's disease, and (2) examine treatment design factors associated with enhanced outcomes following these treatments.

Methods: Eight databases were searched from their start-date up to January 2017 using the key terms *Parkinson's Disease* and *augmented visual feedback*. Two independent raters screened the abstracts and full articles for inclusion. Relevant data were extracted and summarized, and methodological quality of accepted articles was assessed.

Results: Eight single-group studies and 10 randomized control trials were included in the review. Augmented visual feedback-based treatments resulted in improved outcomes with small to large effect sizes post treatment for the majority of impairment, activity, participation, and global motor function measures, and these improvements were often superior to traditional rehabilitation/education programs. Enhanced treatment outcomes were observed in studies that provided large amounts and high intensities of treatment; gamified feedback; and provided knowledge of performance feedback in real-time on 100% of practice trials.

Conclusion: Augmented visual feedback appears to be a useful motor rehabilitation tool in Parkinson's disease; however, high-quality, rigorous studies remain limited. Future studies should consider factors that enhance rehabilitation outcomes when designing augmented visual feedback-based interventions.

Keywords: Parkinson's disease, motor rehabilitation, augmented visual feedback, systematic review

Implications for Rehabilitation

- Augmented visual feedback is a useful tool for motor rehabilitation in Parkinson's disease; augmented visual feedback-based treatments are often superior to traditional programs.
- These treatments are associated with improved outcomes in impairment, activity, participation, and global motor function domains.
- Rehabilitation professionals can optimize their use of augmented visual feedback-based treatments by providing large amounts and a high intensity of treatment, gamifying feedback, and providing knowledge of performance feedback in real-time and at a high frequency.

Introduction

Parkinson's disease (PD) is a progressive neurodegenerative disease characterized by four primary motor symptoms, namely resting tremor, rigidity, bradykinesia, and postural impairment [1]. In spite of advances in pharmaceutical and surgical treatments in PD, individuals develop progressive motor impairments, resulting in complex gait dysfunction (i.e., freezing of gait, shuffling and festination), postural instability, dyskinesia, dystonia, micrographia, dysarthria, and dysphagia [1–3]. As a result, patients experience lack of independence, inactivity, social isolation, and ultimately, a reduced quality of life [4]. Support for rehabilitation therapies in the area of motor impairment is growing [5,6] to enhance personal wellbeing as well as to reduce the economic impact of the disease on society [7].

Physio-, occupational, speech, and swallowing therapies aim to reduce motor impairments and maximize functional ability through rehabilitation. Clinical guidelines for professionals that deliver these therapies outline goals for best practice when addressing motor impairments in PD. Specifically, physiotherapy aims to normalize body posture, stimulate reaching and grasping movements, improve balance and gait, prevent inactivity, preserve or improve physical capacity (aerobic capacity, muscle strength, and joint mobility), improve transfers, and prevent falls [8]. Occupational therapy focuses on improving or maintaining hand and arm function [9]. Speech-language therapy aims to improve patients' speech intelligibility as well as to remediate the impairments associated with swallowing, chewing, and saliva management [10]. Despite best practice guidelines, evidence for the effectiveness of rehabilitation therapies in PD remains limited.

Identifying treatment techniques and developing novel treatments is challenging in PD due to the complex disease pathophysiology [11]. Among the most relevant considerations,

individuals with PD experience reduction in motor learning abilities due to the central role of the basal ganglia in motor learning [12,13]. While studies have shown that individuals with PD can successfully acquire or re-acquire motor skills, they do so at a slower rate than their healthy peers [14,15]. Further, implicit motor learning mechanisms, which rely on motor practice rather than declarative memory, are particularly impaired in PD [16]. As a result, patients with PD appear to benefit from a lot of practice, and explicit methods of motor learning, particularly at the later stages of motor learning when skill transfer occurs [11]. One of the most challenging aspects of rehabilitation is to motivate clients to perform an adequate number of trials during training to achieve sustainable improvements in their motor control. Motivation is yet another challenge that is pronounced in PD, where the dopamine-dependent circuits for motivation are affected [17]. Effective therapies need to be highly motivating in order to engage patients in the process of rehabilitation. Finally, individuals with PD become more dependent on external visual stimuli to execute or learn motor patterns [18–20]. The addition of visual feedback may help to compensate for proprioceptive deficits observed in PD during motor tasks [21–23].

Rehabilitation science turned to technology and paradigms based on augmented visual feedback to enhance learning, increase engagement and improve treatment outcomes [24]. Augmented feedback is defined as “extrinsic feedback provided to a learner” that “supplements the information that is naturally available” [25,p.39], for example, providing an individual with information regarding their step length during walking [26], or tongue movements during speech [27]. Augmented visual feedback has been shown to enhance motor learning in healthy and disordered populations [e.g., stroke; 28]. It engages visual sensory channels and can make the learning process more explicit by providing visual information regarding the outcome of movement and movement characteristics, termed knowledge of results and knowledge of

performance, respectively [29]. In PD, there has recently been a surge in a number of studies reporting novel therapies with augmented visual feedback, particularly in the domain of physiotherapy. The goal of this study is to comprehensively review this literature, evaluate the outcomes of these novel interventions, and identify common factors associated with enhanced outcomes in these studies.

A number of treatment design factors have been associated with enhanced motor learning and improved outcomes in the rehabilitation literature. These factors include (1) the amount of treatment [30]; (2) the intensity of the treatment schedule [31]; (3) gamification of feedback [24]; (4) nature of feedback (i.e., knowledge of results vs. knowledge of performance) [32]; (5) timing of feedback (e.g., real-time vs. delayed) [33]; and (6) frequency of feedback (e.g., every trial vs. summary of five trials) [34]. Some of these factors have been examined in experimental studies of motor learning in PD. For example, in a group of patients with PD with gait abnormalities, a treadmill training program showed better outcomes following low-to-medium intensity (2-3 times/week) than a high intensity schedule (5 times/week) [35]. Further, reduced frequency of feedback enhanced the retention of motor skills for a hand-positioning training task [36] and a speech-timing task [37]. Whereas often not experimentally manipulated within treatment studies, these factors have been implicitly incorporated into the design of rehabilitation programs, and are important to examine across studies because they may significantly affect their study outcomes.

The purpose of this systematic review of literature was to (1) evaluate the effectiveness of augmented visual feedback-based treatments as used for rehabilitation of motor skills in PD, and (2) examine the effect of treatment design factors associated with enhanced treatment outcomes in these studies. These findings are expected to provide future directions for the development and

implementation of augmented visual feedback approaches for motor rehabilitation in adults with PD.

Method

Operational Definitions

Operational definitions, determined a priori, guided the search and included: *Augmented visual feedback*, as movement-related information presented by an external source in the visual modality, including knowledge of results – information related to the outcome of movement - and/or knowledge of performance – information related to the quality of movement [38]; *Motor rehabilitation*, as any intervention that focused on the recovery of motor skill, including but not limited to, balance, gait, hand-writing, speech and swallowing.

Search Strategy

Eight databases were searched from their inception to January 11th, 2017, including MEDLINE, MEDLINE In-Process and Other Non-Indexed Citations, Embase, Cumulative Index to Nursing and Allied Health Literature, Allied and Complimentary Medicine Database, PsycINFO, Cochrane Database of Systematic Reviews, and Cochrane Central Register of Controlled Trials. The start-date varied by database, with the earliest beginning in 1806 (PsychINFO). The key search terms were *Parkinson's disease* combined with *augmented visual feedback* or associated terms (such as sensory feedback, visual feedback, knowledge of results, knowledge of performance). The search terms were adapted for each database (for example, MeSH headings in MEDLINE vs. subject headings in the Cumulative Index to Nursing and Allied Health Literature. See supplementary table S1 for the search strategy used per database. Additionally, the reference lists of pertinent articles (i.e., related review articles and included studies) were examined to ensure that all relevant articles were considered for review.

Inclusion and Exclusion Criteria

This review was limited to studies from peer-reviewed sources that examined the benefit of augmented visual feedback in motor rehabilitation in adults with a diagnosis of PD, regardless of outcome type. Studies were excluded if they (1) had no abstract; (2) targeted animal/ non-human subjects; (3) did not include treatment; (4) did not utilize augmented visual feedback; (5) did not compare performance either within subjects pre-post treatment, or between experimental and control groups post treatment; or (6) were focused on instrument development or validation; (7) were case studies. Tutorials, educational reports, reviews, book chapters, bibliographies, study proposals, and commentaries were also excluded from the review.

Using these criteria, two raters (EK and SS) independently screened each title and abstract for inclusion. Each abstract was either coded as "accept" or "reject" with reason specified. The raters discussed and reached consensus on any differences in abstract coding. For all accepted abstracts, full articles were assessed using the same exclusion criteria.

Data Extraction

The first author (EK) conducted data extraction from accepted full-texts in order to characterize the included studies and identify study outcomes. The extracted data pertained to study design, participants (i.e., sample size, age, sex, disease duration, disease severity), intervention (i.e., setting, motor skill targeted, treatment schedule, description of intervention/technology, augmented feedback modalities, and gamification, content, nature, timing, and frequency of feedback), and timing of follow-up assessment (if applicable). In addition to these characteristics, all outcome measures reflecting motor impairment, motor function, quality of life and associated findings were recorded.

Critical Appraisal

Risk of bias was evaluated based on Cochrane's Grades of Recommendation, Assessment, Development, and Evaluation approach [39]. The key areas were specifying clinical history (i.e., age, sex, aetiology, severity), blinding of outcome assessor, addressing incomplete outcome data (e.g., documenting and providing reasons for study attrition), selectively reporting outcomes (e.g., reporting data from all outcomes outlined in method), reporting point and variability measures (e.g. mean and standard deviation in table or graph form), conducting appropriate statistical analysis (e.g., conducting omnibus testing and correcting for multiple comparisons when necessary), and examining treatment generalization (i.e., examining functional use of treatment beyond target behaviour, such as, activities of daily living, quality of life, global motor function). In addition to these areas, randomized control trials (RCTs) were also examined for evidence of: (1) sequence generation when randomizing participants into experimental and control groups; (2) allocation concealment to ensure that the person enrolling participants could not foresee group assignment; (3) equivalence of intervention groups at baseline on one measure of disease severity and one primary outcome measure; (4) following intention-to-treat principles, where all participants are included in the analysis and analyzed in the groups to which they were randomized; and (5) reporting results between intervention groups. Blinding of participants or treatment personnel was not considered possible, given the behavioural nature of the intervention under review. The key areas were rated as having a high, low, or unclear risk of bias by two independent authors (EK, SS), and differences in ratings were discussed and resolved by consensus.

Data Analysis

Findings across studies were examined descriptively. First, the outcome measures were characterized according to the core levels of the International Classification of Functioning,

Disability, and Health framework [40] (i.e., impairment, activity, and participation), and an additional category was included for measures examining a change in global motor function. Then, all outcome measures were combined across studies to provide counts of measures that demonstrated (or did not demonstrate) an effect of treatment. The measures were combined because the studies varied widely in the measures they employed. In order to summarize the data in a manner that allowed for examination of heterogeneous measures across studies, we calculated, whenever possible, effect sizes for each outcome using Cohen's *d* [41], or extracted effect sizes that were provided. The comparisons targeted were: (1) within-group effects for single group designs; and (2) between group effects for RCTs. We operationalized a positive effect as $d > 0.2$, a negative effect as $d < -0.2$, and no effect as $d < |0.2|$ [41]. Finally, the effect of treatment design factors on treatment outcomes was examined by comparing the outcomes of RCTs relative to the design factors of their intervention. As before, effect sizes were used to determine measures that showed a positive, negative, or no effect.

Results

Study Identification

The database search identified 773 articles related to the use of visual feedback in individuals diagnosed with PD. An additional 10 articles were identified for inclusion by manually checking reference lists of related studies. Following duplicate removal, 456 unique citations were screened using the inclusion/ exclusion criteria described above. Fifty-eight articles were accepted for full-text review and a final 18 articles met all inclusion criteria (see figure 1). Percent agreement between the two independent raters on rejecting articles before reconciliation was 91% at the abstract level, and 81% for full-texts. All disagreements between raters were successfully discussed and resolved by consensus.

Two of the included articles analyzed data from the same dataset [42,43]. The authors implemented different study designs (pre-post single group design vs. RCT) and focused on different outcome measures for both articles. The outcome data from both reports are summarized separately for this review.

[Please insert figure 1 about here]

Study Characteristics

Table 1 summarizes the study characteristics of the 18 included articles, stratified by study design.

Study Design

Eight articles used single group designs [43–50] and the remaining ten articles were RCTs [42,51–59]. All RCTs included an active control group receiving traditional intervention or a comparable intervention without augmented visual feedback. Additionally, two RCTs included an inactive third control group who participated in a falls-prevention education program [53] or received no intervention [56].

Participants

Sample sizes across articles ranged from 10 to 51 individuals diagnosed with PD, and included both male and female participants. In addition to participants with PD, two articles included a healthy control group [43,50], and one article included a group of stroke survivors [51]. Across studies, the average age of participants with PD ranged from 61.1 to 71.5 years, and the average reported time since diagnosis ranged from 3.4 to 10.2 years. Seventeen of the included articles reported measures of disease severity, indexed by the Hoehn and Yahr scale [60] or by the motor part of the Movement Disorder Society - Unified Parkinson's Disease Rating Scale [61]. Disease severity on the Hoehn and Yahr scale ranged from unilateral involvement only to mild-moderate

bilateral disease with some postural instability (average range: 1.5-3). On the Unified PD Rating Scale, average motor scores indicated mild to moderate impairment (average range: 15.9-28.5). The active nature of the majority of interventions excluded participants with more severe symptoms who were unable to ambulate specified distances (for example, 100 feet, or household distances). Most studies recruited participants with some range of disease severities, however, one study exclusively recruited participants with a Hoehn and Yahr score of 2 [45]. Participants with PD were tested while in the "on" stage of their medication; two studies did not report medication status [51,52].

Intervention

Thirteen articles provided information about the intervention setting; eight interventions were conducted in clinics [42–44,46,51,56–58], four were home-based [47,49,50,55], and a single study combined laboratory- and home-based interventions [59].

Balance was the most frequently targeted motor skill (n = 11), while the remaining articles targeted gait [48,51]; balance and gait [59]; muscle strength, coordination and gait [53]; swallowing [44]; and general motor skills [45,54].

Interventions were conducted in 10-84 sessions (*mean* = 21.53, *SD* = 18.44) over 2-12 weeks (*mean* = 6.24, *SD* = 2.65), and testing in all studies was performed pre and post intervention. Additionally, 10 articles assessed maintenance of intervention effects from 2-52 weeks following intervention [42–45,53–59].

Visual feedback was provided by the Nintendo Wii in 11 articles [42,43,45–50,52–54], custom built software in four articles [51,55,56,58], the Smart Balance Master in two articles [57,59], and the Myospace surface electromyography biofeedback device in one article [44]. In addition to visual feedback, the Nintendo Wii Fit provided auditory feedback, while the

Nintendo Wii Sports provided both auditory and vibro-tactile feedback. Two articles also incorporated verbal feedback during training [46,59]. The majority of articles (n = 15) did not report details regarding the presentation of verbal feedback during training.

Feedback was gamified in most articles (n =13), by using either commercially available games from Nintendo Wii (e.g., “Ski Slalom”, “Balance Bubble”) or custom-written software. Non-gamified feedback involved showing participants an surface electromyography signal regarding the time and amplitude of submental muscle contraction during swallowing [44]; a kinematic signal regarding the timing, location, and amplitude of ground reaction forces during gait [51]; or accuracy scores of a stepping or reaching task [59].

The nature of feedback was most commonly knowledge of performance (n = 16). Information about accuracy of performance conveyed knowledge of results feedback only [59]. One article did not provide information about gamification or the nature of feedback employed [57].

Visual feedback varied in timing of presentation and frequency across articles. Typically, visual feedback was presented in real-time while participants were practising the motor skill (n = 15). The remaining articles used terminal feedback following the completion of each trial [59], delayed feedback after a few trials [51], or a combination of both real-time and terminal feedback [57]. Details of feedback frequency were not explicitly stated for the studies using Wii technology, but the frequency was assumed to be 100% given the typical use of the technology. Examined across all articles, feedback was usually provided on 100% of practice trials (n = 16). Only one article reduced the frequency of feedback to approximately one third of the treatment time [51], and one article did not provide information regarding feedback frequency [57].

[Please insert table 1 about here]

Methodological Quality

Two independent raters had good agreement (83%) in appraising methodological quality of studies. All differences in ratings were discussed and successfully resolved by consensus. The risk of bias assessment for all studies is shown in table 2. All single group studies provided point and variability measures for at least one outcome measure, and reported data from all outcomes were stated a priori. The majority of single group studies (n = 7/8) also provided complete clinical history and assessed for evidence of generalization [44–50]. Only four of the eight single group studies clearly addressed study attrition [i.e., incomplete outcome data; 45,46,49,50], only two studies implemented appropriate statistical analysis [44,49], and none reported blinding of the outcome assessor.

For all RCTs, point and variability measures for at least one outcome measure were reported, in addition to data from all outcomes that were reported in the study methods. The majority of RCTs (n = 9/10) specified a complete clinical history of their participants [42,51,53–59]. Eight of the ten RCTs adequately described their sequence generation process and reported blinding of the outcome assessor [42,53–59]. Eight of ten RCTs also demonstrated that the intervention groups were equivalent at baseline and presented results for experimental and control groups [42,51–53,55,56,58,59]. Seven studies reported reasons for study attrition and conducted appropriate statistical analyses, while six studies assessed for evidence of generalization [42,51,53,55,56,58,59]. Only four RCTs, however, reported analyzing data using the intention-to-treat principles [55,56,58,59] and only three studies clearly described if and how allocation concealment was conducted [53,58,59].

[Please insert table 2 about here]

Summary of Findings

Summary of the Outcome Measures by Type

Figure 2 shows the distribution of outcome measures by type across articles. A similar distribution in outcome measure classification was observed for the single group and RCT studies. Activity-level measures were the most prevalent, captured in 17/18 articles [42–53,55–59]. Half of the articles examined change at the impairment level [9/18; 42,44–46,49,51–53,58], while participation level measures were rarely examined [4/18; 44,45,54,55]. Measures of global motor function were assessed in 6/18 articles [42,45,47,48,55,58].

[Please insert figure 2 about here]

Treatment Effect

The treatment outcomes of the studies are summarized in tables 3-5. Fourteen articles provided effect sizes or raw data from which effect sizes could be derived. The total number of measures by category is shown in column 2 (table 3 and 4), and outcome measures with effect sizes ($d >$ |0.2|) are included in column 3. All effect sizes are reported with positive or negative signs indicating improvement ("+") or decline ("-") in performance for within group effects, and enhanced ("+") or reduced ("-") benefit of augmented visual feedback-aided treatment compared to a control treatment for between group effects. Figures 3 and 4 provide a summary of the effects of treatments immediately post treatment (figure 3) and at follow-up (figure 4).

Within Group Effect. Five of eight articles reporting within group effects included sufficient data to estimate the magnitude of effect size (table 3). Above threshold improvements were observed for 76% of all measures (figure 3), including measures of impairment (i.e., balance centre of pressure) and activity (i.e., static and dynamic balance; mobility; gait; upper extremity speed and coordination; fall risk) [45–47,49]. Generalization of treatment effects was also observed for measures of activities of daily living, participation (i.e., quality of life) and global motor function

[45–49]. One measure of depression showed a decline in rating post treatment [46]. The remaining measures (21%) capturing change at the activity level did not meet the threshold for change post intervention; these measures typically examined performance in areas that were not directly targeted during intervention, including upper extremity dexterity [45], balance confidence [46,49], and balance centre of pressure with eyes closed and feet together [49].

Only one of the articles examined performance four weeks post intervention (figure 3) and showed maintenance of treatment effects on measures of impairment, activity, participation and global motor function [45]. At the follow-up time point, performance in activities of daily living had returned to pre-treatment levels.

[Please insert table 3 about here]

[Please insert figure 3 about here]

Between Group Effect. Nine of 10 RCTs provided data to calculate the magnitude of treatment effect between experimental and active control groups (table 4). Approximately half of all measures (48%) indicated an enhanced benefit of augmented visual feedback-aided treatments immediately post intervention (figure 4). The remaining measures showed reduced (23%) or equivocal benefit of augmented visual feedback-based treatments (29%). Inconsistent results (enhanced and reduced benefit) were reported across studies and muscle groups for impairment level measures, such as muscle strength and range of movement [51,53]. Similarly, study-dependent findings were reported for measures of activity; enhanced, reduced and equivocal findings were found for measures of static and dynamic balance, mobility, and gait [42,51–53,55,57–59]. Generalization of treatment effect to activities of daily living, cognition, fatigue, quality of life and global motor function was either enhanced for the experimental group, or similar to the control group [42,52,54,55,58].

Six articles examined the maintenance of treatment effects, with the majority of effects being maintained from 2-12 weeks post intervention [42,53,55,57,58,59], while one study showed maintenance on activity-level measures 12 months post intervention [59] (figure 3). Reports of both enhanced and reduced benefit of augmented visual feedback-based treatments, however, were reported for global motor function when assessed at follow-up [42,55,58].

One study provided data to calculate the magnitude of treatment effect between an experimental group and an inactive control group who received falls prevention education (table 4). Post-intervention measures of impairment (i.e., muscle strength) and activity (i.e., balance, gait) were enhanced in the experimental group [53]. At follow-up assessment four weeks post intervention, the benefit of augmented visual feedback-aided treatment was maintained for all measures.

[Please insert table 4 about here]

[Please insert figure 4 about here]

Analysis of Treatment Design Factors in RCTs

Figure 5 summarizes the analysis of treatment design factors in RCTs comparing experimental to active control groups. For continuous measures (amount and intensity of treatment), the distribution of data was examined to identify clusters. Studies were then categorized as having small (≤20 hours) or large (>20 hours) amounts of treatment, and low (≤3 sessions/week) or high (>3 sessions/week) treatment intensities. One RCT did not provide details that pertained to gamification, nature, or timing of feedback, and was excluded from those analyses [57].

The majority of RCTs used a small amount of treatment time at a low intensity. Six of the seven studies that implemented a small amount of treatment also delivered the treatment at a low intensity. Studies with large amounts and high intensities of treatment showed a trend for greater

benefits of augmented visual feedback as compared to treatments delivered in small amounts and at low intensities.

Most RCTs also implemented gamification of feedback and provided knowledge of performance information in real-time and on 100% of practice trials. Gamification of feedback resulted in a higher proportion of enhanced benefits, compared to studies with non-gamified feedback. A trend for greater benefits was also observed for studies providing knowledge of performance information, relative to a single study that provided knowledge of results. Real-time feedback, either alone or combined with terminal feedback, led to a greater proportion of enhanced benefits, compared to providing only terminal or delayed feedback. Additionally, studies implementing 100% feedback frequency showed a larger percentage of measures with enhanced benefits than a study with a reduced feedback schedule.

[Please insert figure 5 about here]

Discussion

The overall aim of this study was to examine the effectiveness of augmented visual feedback-based approaches on motor rehabilitation in Parkinson's disease and to identify the factors that might be associated with better treatment outcomes. A detailed analysis of the data from single-group studies and RCTs revealed that augmented visual feedback-based treatments led to clearly improved outcomes post treatment, as well as superior outcomes as compared to traditional rehabilitation and education programs. Instances of reduced and equivocal benefits of such treatments, however, were also reported.

Many of the included studies were rated, however, as having a high or unclear risk of bias on key areas of methodological quality. Only two RCTs were rated as having a low risk of bias for all key areas. Their results showed enhanced, reduced, and equivocal benefits of augmented

visual feedback-aided treatments on measures of impairment, activity and global motor function as compared to traditional rehabilitation methods [58,59]. The effectiveness of augmented visual feedback-based approaches needs to be considered in relation to the characteristics of the participants in the included studies, as well as the implementation of different treatment enhancing factors. Examining the outcome data in this way can lead to recommendations for treatment candidacy as well as identifying factors that may be affecting treatment outcomes.

Participant Characteristics

Both the presentation and progression of symptoms in PD are notably variable across patients [1], yet the participants in the included studies represented a relatively homogenous group of patients in terms of age and disease severity. Most studies recruited those with mild-moderate disease severity without cognitive impairment. Noteworthy is one RCT that included older, more severely impaired participants (i.e., moderate impairment), which showed enhanced benefit of augmented visual feedback-based interventions over traditional rehabilitation immediately post treatment [55]. This might suggest that patients in the later stages of PD, who typically have greater difficulties with implicit motor learning, may benefit to a great extent from augmented visual feedback to improve their control of movement [11].

Treatment Design Factors

A number of factors have been identified as influencing the outcomes of rehabilitation. Among these factors are the amount and intensity of therapy, the use of engaging technology and motivating games, and the nature, timing, and frequency of augmented visual feedback.

Generally, studies that provided large amounts of treatment did so at a high intensity, and therefore, in the context of this review, it is not possible to delineate the effect of these two treatment factors independently. When augmented visual feedback-based treatments were

provided in large amounts at high intensities, more enhanced benefits of treatment were observed compared to interventions provided in small amounts at low intensities. This finding is in contrast to a previous study of treadmill training in PD (without augmented feedback) that showed better outcomes at lower treatment intensities [35]. The amount of treatment in Pelosin et al.'s study [35], however, was small (i.e., 10 hours). It is possible that a high intensity of treatment might be most effective when combined with a large amount of treatment.

The majority of RCTs used gamified visual feedback - via the Wii or custom-built software - and showed enhanced benefit compared to traditional rehabilitation. In contrast, inconsistent results were found for the non-gamified approaches [51,59]. When feedback was not gamified, it was presented graphically as a time history (e.g., muscle force during swallowing, ground reaction force during gait) or as an accuracy score. This information may be challenging to interpret for a non-expert user. Further, non-gamified approaches may lack the engagement of a game that has intuitive representations of movement and structured levels of difficulty. These early results indicate that gamification is a beneficial factor of the visual feedback systems, and may promote greater treatment adherence and potentially better outcomes than traditional rehabilitation [24]. Availability of commercial solutions that may have established usability and are familiar to the general public (e.g., patients and caregivers) offer a particularly attractive option for rehabilitation of motor skills.

Most of the reviewed studies provided knowledge of performance feedback during treatment and showed a benefit of these treatments over a single intervention that provided knowledge of results feedback. Knowledge of performance feedback may have been more beneficial in conveying information necessary for training complex motor skills, such as those targeted in the studies, compared to feedback focused only on the outcome of movement.

Previous studies examining the effect of knowledge of performance versus results feedback on motor learning in healthy populations have also shown a benefit of knowledge of performance over knowledge of results [62].

The majority of studies implemented real time feedback in their design and showed better outcomes than the terminal or delayed feedback studies. Real-time or concurrent feedback has been shown to be beneficial to motor learning in healthy adults when it provides an external focus of attention [63,64]. However terminal or delayed feedback can allow for greater intrinsic processing of feedback and thus, better retention of motor skill [33]. Real-time feedback may have a dual effect in facilitating motor learning in PD; as the visual information is always present, patients may be benefitting from cueing of movement, as well as from the feedback about how the movement was performed. Notably, the same two studies that used terminal or delayed feedback also used non-gamified feedback as discussed above and these two design factors may have interacted.

Even though most studies provided feedback 100% of the time during training, gains were still apparent post intervention when feedback was removed, suggesting that participants were not dependent on the feedback in order to carry out the motor skill [see Guidance Hypothesis; 65]. In contrast, a study that provided feedback on a reduced schedule (for approximately one third of the treatment session) showed reduced benefit of visual feedback when compared to traditional rehabilitation on measures of impairment, and inconsistent benefits on measures of activity. The advantage of high frequency over low frequency feedback differs from previous studies of novel motor skill learning in PD [36,37]. While feedback frequency was not experimentally manipulated during the studies, the significant benefits in studies with 100%

feedback frequency suggest that individuals with PD can transfer their learning to non-feedback contexts.

Limitations of Existing Literature

The findings from this systematic review showed that high-quality, rigorous studies of the effect of augmented visual feedback-based treatments on motor rehabilitation in PD remain limited, however, this area is a growing topic of research. The majority of identified studies were in the physiotherapy domain, targeting motor skills such as balance, gait, and muscle strength. Although the search aimed to identify studies relevant to all rehabilitative disciplines, only one study focused on the rehabilitation of swallowing. A number of studies examining augmented visual feedback in the context of writing or speech production in PD either did not study these skills in the context of rehabilitation [e.g., 27,66], or augmented visual feedback was incorporated as a small component of a wider treatment program in a single group study [e.g., 68]. A recent systematic review of rehabilitative therapies in PD also identified a greater number of RCTs for physiotherapy (n = 25) compared to occupational therapy (n = 4) and speech-language pathology (n = 10) [5].

Even though the aim of all studies was to assess the effect of an intervention, methodological descriptions of the interventions were often not detailed enough to be replicated by another research group. Many of the interventions involved multiple components (e.g., a variety of video games), or included additional training tasks that were supplementary to the experimental rehabilitation. As a result, it was difficult to assess which components were effecting change, or whether the augmented visual feedback-based treatment alone was effective.

The majority of studies aimed to capture change in activity-based clinical measures. While these measures often show strong and important relationships to functional change for

participants, they do not capture the underlying change at a physiological level. Only four studies examined change at the participation level, even though a number of valid PD-specific instruments are available to measure quality of life in this population, such as the Parkinson's Disease Questionnaire-39 item version [68]. The inclusion of quality of life measures would offer a broader social perspective on the potential effects of augmented visual feedback-based interventions for patients with PD.

A number of participant factors may have played a role in the treatment outcomes but were often not accounted for in the included studies. First, the RCTs rarely sex-matched experimental and control groups, or statistically controlled for sex in the analyses, even though previous studies suggested sex differences in the clinical presentation of PD [69–71], which may have affected participants' performance. Another consideration is that an increased familiarity with technology before treatment may have benefitted participants, yet only three studies considered this factor by excluding participants who had experience playing the Wii. Further, while intact vision is an important pre-requisite of using visual feedback systems, only half of the studies specified normal or corrected-to-normal vision as an inclusion criterion. Finally, when assessing balance parameters in an older population, it is pertinent to remember that hearing loss occurs in 45% of adults over 60 years of age, and is associated with an increased risk of balance impairment and falls [72]. The balance impairment, therefore, may be confounded by a comorbid hearing impairment. Three studies excluded participants with auditory impairment, but did not document how the participants were screened (e.g., by patient report or audiometric testing).

Recommendations for Practice and Future Research

This review indicates that augmented visual feedback may be clinically beneficial for individuals with mild-moderate PD symptoms. When designing visual feedback-based intervention, the

following factors should be considered: large amounts and high intensities of treatment, gamification of feedback, knowledge of performance feedback, real-time feedback, and a high frequency of feedback.

Further high-quality research is needed to assess the effect of augmented visual feedback in the rehabilitation of fine motor, speech and swallowing skills, to identify the "active" ingredients of interventions, and to understand the physiological mechanisms underlying changes in clinical outcomes following treatment. Improved participant descriptions are also needed to control for confounding factors and to assess the applicability of study results. Future studies, and in particular RCTs, would benefit from following the Consolidated Standards of Reporting Trials guidelines when designing studies and disseminating results [73].

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Declaration of interest

The authors report no conflicts of interest.

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Table 1. Study characteristics.

Study	Design	Participants					Intervention						
		N	Sex (M/F)	Age (years, m ± SD)	PD Disease duration (years, m ± SD)	PD Disease severity, m ± SD)	Setting	Motor Skill Targeted	Treatment Schedule	Follow-up Assessment (weeks)	Device/ Intervention Description	Feedback Modalities	Visual Feedback (gamification, content, nature, timing, frequency)
Single Group Designs													
dos Santos Mendes, Pompeu [43]	Pre-post single group design, including comparisons to healthy control group	**Exp:** 16 **Control:** 11	**Exp:** NR; **Control:** matched for gender	**Exp:** 68.6 ± 8.0 **Control:** 68.7 ± 4.1	**Exp:** 4.7 ± 5.4	**Exp:** HY: 1.86 ± 0.33	Clinic	Balance	30 mins (balance) + 30 mins (exercise), 2 days/week, 7 weeks	9	Wii Fit balance board + global exercise Static balance, dynamic balance + stationary gait	Visual, auditory	Gamified; Torso Twist, Single Leg Extension, Rhythm Parade, Table Tilt, Tilt City, Basic Step, Penguin Slide, Obstacle Course, Soccer Heading, Basic Run Plus; KR/KP; real-time on 100% of trials
Esculier, Vaudrin [50]	Pre-post single group design, including comparisons to healthy control group	**Exp:** 11 **Control:** 9	**Exp:** 6/5 **Control:** 5/4	**Exp:** 61.9 ± 11.0 **Control:** 63.5 ± 12.0	**Exp:** 8.5 ± 3.6	**Exp:** UPDRS (Motor III): 18.4 ± 5.4	Home	Balance	40 mins, 3 days/week, 6 weeks	NR	Wii Fit balance board + Wii Sports Balance, yoga + aerobics	Visual, auditory, vibro-tactile	Gamified; Golf, Bowling, Table Tilt, Ski Slalom, Balance Bubble, Ski Jump, Penguin Slide, Deep Breathing, Hula-Hoop; KR/KP; real-time on 100% of trials
Herz, Mehta [45]	Pre-post single group design	20	13/7	66.7 ± 7.2	5.5 ± 4.3	HY: 2 ± 0	NR	Motor (unspecified)	60 mins, 3 days/week, 4 weeks	4	Wii Sport Balance, coordination + full-body motion training	Visual, auditory, vibro-tactile	Gamified; Bowling, Tennis, Boxing; KR/KP; real-time on 100% of trials
Holmes, Gu [49]	Pre-post single group design	15	7/4	63.91 ± 12.05	8.45 ± 3.75	HY: 2.27 ± 0.39 UPDRS (Motor III): 25.18 ± 11.71	Home	Balance	30 mins, 3 days/week, 12 weeks	NR	Wii Fit balance board Balance	Visual, auditory	Gamified; Balance Bubble, Table Tilt, Soccer Heading, Tightrope Tension, Penguin Slide, Ski Slalom, Snowboard Slalom; KR/KP; real-time on 100% of trials
Mhatre, Vilares [46]	Pre-post single group design	10	4/6	67.1; Range: 44-91	6.7; Range: 1-14	HY: Range: 2.5-3	Clinic	Balance	30 mins, 3 days/week, 8 weeks	NR	Wii Fit balance board Balance	Visual	Gamified; unspecified marble, balance, bubble games; KR/KP; real-time on 100% of trials

Zalecki, Gorecka-Mazur [47]	Pre-post single group design	24	17/7	61.8 ± 1.9	9.21 ± 0.94	UPDRS (Motor II): 13.29 ± 0.47 UPDRS (Motor III): 22.42 ± 0.63	Home	Balance	20 mins, twice/day, 6 weeks	NR	Wii Fit balance board + Wii Sport Balance, flexibility, strength + coordination	Visual, auditory, vibro-tactile	Gamified; Ski Slalom, Balance Bubble, unspecified Wii Sport games; KR/KP; real-time on 100% of trials
Athukorala, Jones [44]	Pre-post single group design	10	7/3	67.4 ± 8.6	6.6 ± 4.0	HY: 2.7 ± 0.4	Clinic	Swallowing	60 mins, 5 days/week, 2 weeks	2	Myopace surface electromyography, submental muscles Dry swallows	Visual	Not gamified; signal showing amplitude + timing; KR/KP; real-time on 100% of trials
Gonçalves, Leite [48]	Pre-post single group design	15	8/7	68.70 ± 10.20	7.30 ± 3.70	HY: 2.10 ± 0.30 UPDRS (Motor III): 28.5 ± 9.91	NR	Gait	40 mins, 2 days/week, 7 weeks	NR	Wii Fit balance board + exercise Balance + aerobics	Visual, auditory	Gamified; Free Step, Rhythm Step, Slalom Skiing, Jump Skiing, Advanced Skiing, Header, Jump Rope, Segway Circuit, Advanced Circuit, Cycling, Advanced Cycling; KR/KP; real-time on 100% of trials
RCT Group Designs													
Stern [57]	RCT	**Exp:** 10 **Control:** 10	**Exp:** 4/6 **Control:** 7/3	**Exp:** 66.1 ± 6.1 **Control:** 64.8 ± 7.3	**Exp:** 2.85 ± 1.55 **Control:** 4.0 ± 3.32	**Exp:** HY: 1.50 ± 0.33 **Control:** HY: 1.45 ± 0.37	Clinic	Balance	36 mins, 5 days/week, 2 weeks	4	**Exp:** Limits of stability + sit-to-stand training with feedback via Smart Balance Master System **Control:** Traditional rehabilitation (stretching, sitting + standing balance, gait + transfers)	**Exp:** Visual **Control:** NR	NR; related to weight-shifting on force plates; NR: real-time/ terminally, frequency NR
Yen, Lin [56]	RCT	**Exp:** 14 **Active Control:** 14 **Inactive Control:** 14	**Exp:** 12/2 **Active Control:** 12/2 **Inactive Control:** 9/5	**Exp:** 70.4 ± 6.5 **Active Control:** 70.1 ± 6.9 **Inactive Control:** 71.6 ± 5.8	**Exp:** 6.0 ± 2.9 **Active Control:** 6.1 ± 3.3 **Inactive Control:** 7.8 ± 4.2	**Exp:** HY: 2.6 ± .5 UPDRS (Motor III): 15.1 ± 3.2 **Active Control:** HY: 2.4 ± 0.5 UPDRS (Motor III): 15.9 ± 2.4 **Inactive Control:** HY: 2.6 ± 0.4 UPDRS (Motor III): 16.8 ± 5.5	Clinic	Balance	10 mins (warm-up) + 20 mins (training), 2 days/week, 6 weeks	4	**Exp:** Warm-up exercises + dynamic balance training with virtual reality balance training system (Cycling + Health Center of Taichung, Taiwan) **Active Control:** Conventional balance training (static stance, dynamic weight shifting, external perturbations) **Inactive Control:** No training	**Exp:** Visual **Active Control:** NR **Inactive Control:** None	Gamified; 3D Ball-Rolling Game, Indoor-outdoor Virtual Activities; KR/KP; real-time on 100% of trials
Pompeu,	RCT	**Exp:**	17/15	**Exp:**	**Exp:**	HY 1.7 ± 0.5	Clinic	Balance	30 mins	9	**Exp:**	**Exp:**	Gamified; Torso

dos Santos Mendes [42]		16 **Control:** 16	(NR by group)	66.2 ± 8.3 **Control:** 68.6 ± 8.0	5.2 ± 3.4 **Control:** 4.7 ± 5.4	(NR by group)			(balance) + 30 mins (exercise), 2 days/week, 7 weeks		Static balance, dynamic balance + stationary gait training with Wii Fit balance board + global exercise **Control:** Traditional training (static balance, dynamic balance + stationary gait) + global exercise	Visual, auditory **Control:** None	Twist, Single Leg Extension, Rhythm Parade, Table Tilt, Tilt City, Basic Step, Penguin Slide, Obstacle Course, Soccer Heading, Basic Run Plus; KR/KP; real-time on 100% of trials
Pedreira, Prazeres [54]	RCT	**Exp:** 16 **Control:** 15	**Exp:** 11/5 **Control:** 11/4	**Exp:** 61.1 ± 8.2 **Control:** 66.2 ± 8.5	**Exp:** 8.6 ± 4.6 **Control:** 7.3 ± 6.6	**Exp:** HY: 2.5 ± 0.6 **Control:** HY: 2.4 ± 0.7	NR	Motor (unspecified)	10 mins (warm-up) + 40 mins (exercise), 3 days/week, 4 weeks	NR	**Exp:** Warm-up exercise + exercise training with Wii (unspecified) **Control:** Warm-up exercise + traditional physical therapy	**Exp:** Visual, auditory **Control:** NR	Gamified; Games NR; KR/KP; real-time on 100% of trials
Shen and Mak [59]	RCT	**Exp:** 26 **Control:** 25	**Exp:** 3/9 **Control:** 12/11	**Exp:** 63.3 ± 8.0 **Control:** 65.3 ± 8.5	**Exp:** 8.1 ± 4.3 **Control:** 6.6 ± 4.0	**Exp:** HY: 2.4 ± 0.5 **Control:** HY:2.5 ± 0.5	Lab-oratory / home	Balance, gait	Lab: 60 mins, 3 days/week, 8 weeks Home: 20 mins, 5 days/week, 4 weeks	12; 52	**Exp:** 1) Stepping + reaching exercise with computerized dancing system + Smart-Equitest Balance Master 2) Training for response to perturbation on treadmill **Control:** Lower limb strength training Session length: 60 mins (lab); 20 mins (home)	**Exp:** Visual, verbal **Control:** NR	Not gamified; accuracy of timing + amplitude of step + reaching; KR; terminally on 100% of trials
van den Heuvel, Kwakkel [58]	RCT	**Exp:** 17 **Control:** 16	**Exp:** 12/5 **Control:** 8/8	**Exp:** 66.3 ± 6.39 **Control:** 68.8 ± 9.6	**Exp:** Median: 9, IQR: 9.25 **Control:** Median: 8.8, IQR: 9	**Exp:** HY: Median: 2.5, IQR: 1.5 UPDRS (Motor III): Median: 30.8, IQR: 21.5 **Control:** HY: Median: 2.5, IQR: 1.0 UPDRS (Motor III): Median: 28.0, IQR: 17.88	Clinic	Balance	60 mins, 2 days/week, 5 weeks	6	**Exp:** Standing + dynamic training with feedback via forceplate + inertial sensors in custom software **Control:** Sitting + dynamic training	**Exp:** Visual **Control:** NR	Gamified; game corresponded to user's foot placement + upper leg orientation during body lean, stepping + sit-to-stand movement; KR/KP; real -time on 100% of trials
Byl, Zhang [51]	RCT	**Exp:** PD: 7 Stroke: 5 **Control:** PD: 5 Stroke: 7	**Exp:** PD: 3/4 Stroke: 3/2 **Control:** PD: 4/1 Stroke: 2/5	**Exp:** PD: 68.5 ± 3.6 Stroke: 66.2 ± 5.0 **Control:** PD: 70 ± 2.9	**Exp:** PD: 8.7 ± 4.4 Stroke: 10.4 ± 7.8 **Control:** PD: 11.6 ± 5.9	**Exp:** PD: HY: Range: 1-3 Stroke: Fugl-Meyer: 14.5 ± 5.6 **Control:** PD: HY: Range:	Clinic	Gait	90 mins, 12 session, 6-8 weeks	NR	**Exp:** Smart shoes with pressure sensors + smart pants with joint angle sensors Gait **Control:** Gait training	**Exp:** Visual **Control:** NR	Not gamified; signal showing timing, location + amplitude of ground reaction forces; KP; delayed schedule "after a few walking trials" for 1/3 of training

				Stroke: 60.8 ± 5.4	Stroke: 6.6 ± 3.6	1-3 Stroke: 14.9 ± 5.3							session
Lee, Lee [52]	RCT	**Exp:** 10 **Control:** 10	**Exp:** 5/5 **Control:** 5/5	**Exp:** 68.4 ± 2.9 **Control:** 70.1±3.3	NR	NR	NR	Balance	(1) 30 mins + (2) 30 mins + (3) 15 mins (FES), 5 days/week, 6 weeks	NR	**Exp:** (1) Wii, Dance (2) neurodevelopment treatment (3) functional electrical stimulation (FES) **Control:** Neurodevelopment treatment, FES	**Exp:** Visual, auditory, vibro-tactile **Control:** None	Gamified; K-pop Dance Festival; KR/KP; real-time on 100% of trials
Liao, Yang [53]	RCT	**Exp:** 12 **Active Control:** 12 **Inactive Control:** 12	**Exp:** 5/7 **Active Control:** 6/6 **Inactive Control:** 6/6	**Exp:** 64.6 ± 8.6 **Active Control:** 65.1 ± 6.7 **Inactive Control:** 67.3 ± 7.1	**Exp:** 6.4 ± 3.0 **Active Control:** 6.9 ± 2.8 **Inactive Control:** 7.9 ± 2.7	**Exp:** HY: 1.9 ± 0.8 **Active Control:** HY: 2.0 ± 0.8 **Inactive Control:** HY: 2.0 ± 0.7	NR	Muscle strength, sensory integration, gait	45 mins (exercise) + 15 mins (treadmill training), 2 days/week, 6 weeks	4	**Exp:** Yoga, strengthening + balance exercise with Wii Fit balance board + Wii Sport + treadmill training **Active Control:** Traditional rehabilitation (stretching, strengthening + balance exercise) + treadmill training **Inactive Control:** No exercise + fall prevention education	**Exp:** Visual, auditory, vibro-tactile **Active Control:** NR **Inactive Control:** n/a	Gamified; Yoga (sun-salutation, modified lunges, chair pose, tree pose, table top in standing position), strengthening exercises, Football Game, Marble Balance, Ski Slalom, Bubble Balance; KR/KP; real-time on 100% of trials
Yang, Wang [55]	RCT	**Exp:** 11 **Control:** 12	**Exp:** 7/4 **Control:** 7/5	**Exp:** 72.5 ± 8.4 **Control:** 75.4 ± 6.3	**Exp:** 9.4 ± 3.6 **Control:** 8.3 ± 4.1	**Exp:** HY: Median: 3 **Control:** HY: Median: 3	Home	Balance	50 mins, 2 days/week, 6 weeks	2	**Exp:** Static posture + dynamic weight shifting with virtual reality balance training system (Cycling + Health Center of Taichung, Taiwan) **Control:** Traditional Rehabilitation (Static posture + dynamic weight shifting)	**Exp:** Visual **Control:** Verbal	Gamified; Star Excursion, Ball Maze, Table Tilt, Home Yoga, Cooking, Cloth Washing, Car Racing, Park Walking, Apple Catching; KR/KP; real-time on 100% of trials

Note: M/F = Male/Female; Exp = Experimental Group; Control = Control Group; HY = Hoehn and Yahr Scale; NR = Not reported; PD = Parkinson's disease; RCT = Randomized Control trial; UPDRS = Unified Parkinson's Disease Rating Scale.

Table 2. Critical appraisal of risk of bias.

Study	Clinical history specified (age, sex, aetiology, severity)	Sequence generation	Allocation concealment	Groups equivalent at baseline	Blinding of outcome assessor	Incomplete outcome data addressed	Selective outcome reporting	Intention-to-treat analysis	Results between intervention groups reported	Point and variability measures reported for at least one outcome	Appropriate statistical analysis	Evidence for generalization
Single Group Designs												
dos Santos Mendes, Pompeu [43]	✘	n/a	n/a	n/a	-	-	✓	n/a	n/a	✓	-	✘
Esculier, Vaudrin [50]	✓	n/a	n/a	n/a	-	✓	✓	n/a	n/a	✓	✘	✓
Herz, Mehta [45]	✓	n/a	n/a	n/a	-	✓	✓	n/a	n/a	✓	✘	✓
Holmes, Gu [49]	✓	n/a	n/a	n/a	-	✓	✓	n/a	n/a	✓	✓	✓
Mhatre, Vilares [46]	✓	n/a	n/a	n/a	✘	✓	✓	n/a	n/a	✓	✘	✓
Zalecki, Gorecka-Mazur [47]	✓	n/a	n/a	n/a	-	-	✓	n/a	n/a	✓	✘	✓
Athukorala, Jones [44]	✓	n/a	n/a	n/a	✘	-	✓	n/a	n/a	✓	✓	✓
Gonçalves, Leite [48]	✓	n/a	n/a	n/a	-	-	✓	n/a	n/a	✓	✘	✓
RCT Group Designs												
Stern [57]	✓	✓	-	✘	✓	-	✓	-	✘	✓	✘	✘
Yen, Lin [56]	✓	✓	✘	✓	✓	✓	✓	✓	✓	✓	✓	✘
Pompeu, dos Santos Mendes [42]	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓	✓
Pedreira, Prazeres [54]	✓	✓	-	✘	✓	✘	✓	-	✘	✓	✘	✓
Shen and Mak [59]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
van den Heuvel, Kwakkel [58]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Byl, Zhang [51]	✓	-	-	✓	-	✓	✓	-	✓	✓	✓	✘
Lee, Lee [52]	✘	-	-	✓	-	-	✓	-	✓	✓	✘	✓

Liao, Yang [53]	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✘
Yang, Wang [55]	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note:
✓ Low risk of bias
✘ High risk of bias
- Unclear risk of bias
n/a Not applicable to non-randomized control trials

Table 3. Summary of Within-Group Findings

Study	Classification of Measures (n)	Outcome Measures	Effect Size Post Intervention	Effect Size at Follow-Up
Herz, Mehta [45]	Impairment (1) Activity (10) Participation (1) Global Motor Function (1)	Impairment *Hamilton Rating Scale for Depression* Activity *Nottingham Extended ADL Scale* *9-hole peg test - right* *Purdue Pegboard Test – left* *Purdue Pegboard Test – both* *Purdue Pegboard Test – alternating* *Timed tapping test – right* *Timed tapping test – left* *Timed Up and Go* Participation *Parkinson's Disease Questionnaire-39* Global Motor Function *UPDRS*	 +0.98 +0.37 +0.31 +0.51 +0.30 +0.38 +0.61 +0.39 +0.25	 +1.10 +0.38 +0.30 +0.28 +0.27 +0.21 +0.22 +0.32
Holmes, Gu [49]	**I**mpairment (4) Activity (1)	Impairment *Balance Centre of Pressure – eyes open, feet apart* *Balance Centre of Pressure – eyes open, feet together* *Balance Centre of Pressure – eyes closed, feet apart*	 +0.20 +0.20 +0.20	 n/a
Mhatre, Vilares [46]	Impairment (1) Activity (5)	Impairment *Geriatric Depression Scale* Activity *Berg Balance Scale* *Dynamic Gait Index* *Sharpened Romberg Test – eyes open* *Sharpened Romberg Test – eyes closed*	 -0.35 +0.37 +0.98 +0.28 +0.57	 n/a
Zalecki, Gorecka-Mazur [47]	Activity (1) Global Motor Function (1)	Activity *Timed Up and Go* Global Motor Function *UPDRS*	 +2.59 +10.35	 n/a
Gonçalves, Leite [48]	Activity (2) Global Motor Function (1)	Activity *Shwab & England ADL scale* *Functional Independence Measure* Global Motor Function *UPDRS*	 +1.30 +1.49 +1.45	 n/a

Note: The total number of measures by category is shown in column 2. Only data from outcome measures with small ($d \geq .2$), medium ($d \geq .5$) or large effect sizes ($d \geq .8$) shown; ' + ' indicates improvement in performance, and ' – ' indicates decline in performance.
n/a = not applicable; UPDRS = Unified Parkinson's Disease Rating Scale; ADL = Activities of Daily Living.

Table 4. Summary of Between-Group Findings

Study	Classification of Measures (n)	Outcome Measures	Effect Size Post Intervention	Effect Size at Follow-up
Augmented Visual Feedback Treatment vs. Active Control Group				
Stern [57]	Activity (2)	Activity		
		Timed Up and GO	+0.58	+1.12
		Functional Reach Task	+0.40	+0.94
Pompeu, dos Santos Mendes [42]	Impairment (1) Activity (3) Global Motor Function (1)	Activity *Unipedal Stance Test (eyes open)* Global Motor Function *UPDRS*	+0.23	+0.23 -0.22
Pedreira, Prazeres [54]	Participation (1)	Participation *Parkinson's Disease Questionnaire-39*	+0.72	n/a
Shen and Mak [59]	Activity (6)	Activity *Activities-Specific Balance Confidence Scale* *Limits of Stability – velocity* *Limits of Stability – end-point excursion* *Gait velocity* *Stride length*	 +0.38 -0.32 -0.23 +0.61	 +0.35 (4 wks); +0.38 (52 wks) +0.59 (4 wks); +0.24 (52 wks) +0.38 (4 wks); +0.50 (52 wks)
van den Heuvel, Kwakkel [58]	Impairment (4) Activity (8) Global Motor Function (1)	Impairment *Hospital Anxiety and Depression Scale – anxiety* *Hospital Anxiety and Depression Scale – depression* Activity *Functional Reach Test* *Berg Balance Scale* *Single Leg Stance – preferred* *Single Leg Stance – non-preferred* *Gait speed* *Gait step length* *Falls Efficacy Scale* *PDQ-39 (mobility subscore*) Global Motor Function *UPDRS*	 -0.21 -0.42 +0.28 +0.23 +0.31 +0.51 +0.55 +0.29	 +0.28 +0.34 0.39 0.48 0.22 0.36 0.27 0.22
Byl, Zhang [51]	Impairment (4) Activity (8)	Impairment *Muscle strength – affected side* *Muscle strength – unaffected side* *ROM – affected side* *ROM – unaffected side* Activity *Step length* *Tinetti Gait Assessment* *6 min walk* *Dynamic Gait Index* *Timed Up and Go* *Berg Balance Scale*	 -0.30 -0.30 -0.56 -0.76 -0.27 -0.32 -0.94 +0.23 +0.86 -0.89	 n/a
Lee, Lee [52]	Impairment (1) Activity (2)	Impairment *Beck Depression Index* Activity *Berg Balance Scale* *Modified Barthel Index*	 +0.99 +0.62 +0.91	 n/a
Liao, Yang [53]	Impairment (6) Activity (6)	Impairment *Muscle strength* *- hip flexors (f) + extensors (e)* *- knee f + e* *- ankle dorsiflexors (d)+ plantarflexors (p)* Activity *Gait velocity* *Stride length* *Functional gait assessment* *Sensory Organization Test (somatosensory)* *Sensory Organization Test (vision)* *Sensory Organization Test (vestibular)*	 -0.29 (f) +0.44 (e) -0.23 (f) +0.24 (e) -0.23 (d) +0.31 (p) +0.32 +0.48 +0.47 +0.56 +0.76	 -0.51 (f) +0.29 (e) -0.31 (f) +0.31 (p) +0.30 +0.28 +0.54 +0.46 +0.67
Yang, Wang [55]	Activity (3) Participation (1) Global Motor Function (1)	Activity *Dynamic Gait Index* Global Motor Function *UPDRS*	 +0.45 +0.46	 -0.40
Augmented Visual Feedback Treatment vs. Inactive Control Group				
Liao, Yang [53]	Impairment (6) Activity (6)	Impairment *Muscle strength* *- hip flexors (f) + extensors (e)* *- knee f + e* *- ankle dorsiflexors (d)+ plantarflexors (p)*	 +0.68 (f) +1.07 (e) +0.61 (f) +1.13 (e) +1.16 (d) +1.21 (p)	 +0.71 (f) +0.76 (e) +0.57 (f) +0.91 (e) +1.31 (d) +1.05 (p)

Activity		
Gait velocity	+1.06	+0.75
Stride length	+0.97	+0.96
Functional gait assessment	+1.86	+1.83
Sensory Organization Test (somatosensory)	+0.58	+0.66
Sensory Organization Test (vision)	+1.34	+1.29
Sensory Organization Test (vestibular)	+1.67	+1.43

Note: Only outcome measures with small (d ≥ .2), medium (d ≥ .5) or large effect sizes (d ≥ .8) shown; ' + ' indicates experimental group performance was enhanced compared to control group, and ' – ' indicates experimental group performance was reduced relative to control group.
n/a = not applicable; UPDRS = Unified Parkinson's Disease Rating Scale; Wks = weeks.

Figures and Captions

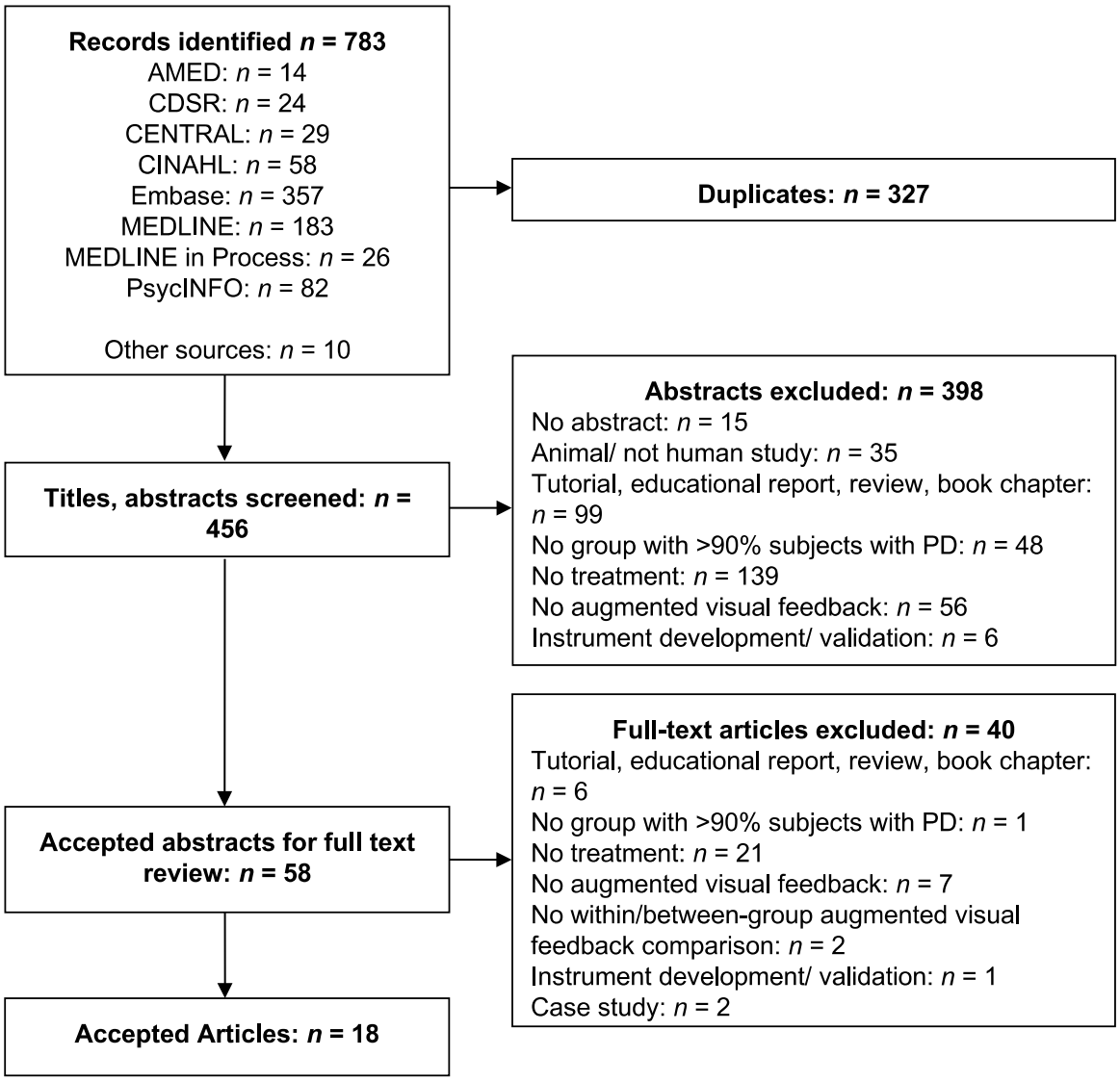

Figure 1. Flow chart illustrating search strategy and screening process.

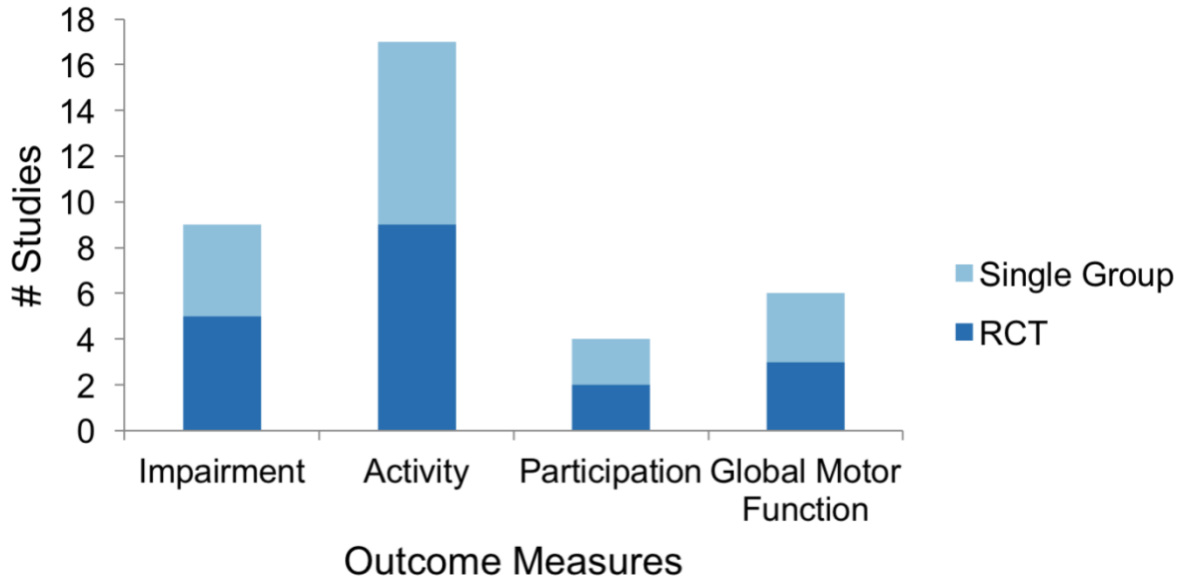

Figure 2. Distribution of outcome measures by type across all studies. Outcome measures are classified by the core levels of the International Classification of Functioning, Disability, and Health, and global motor function.

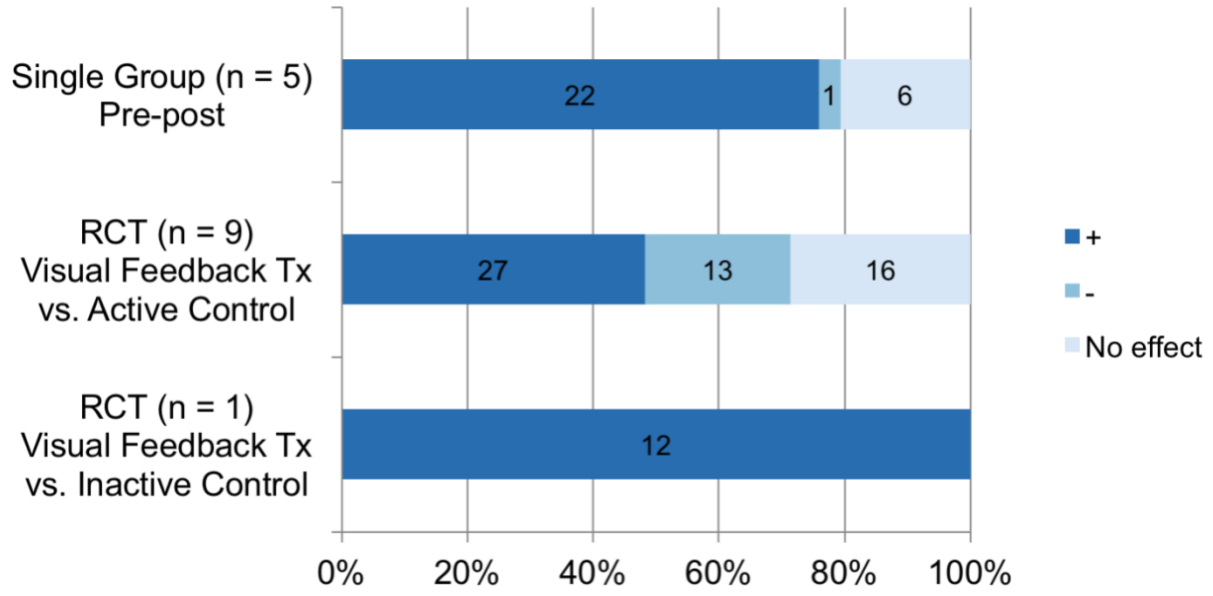

Figure 3. The summary of measures showing positive (+), negative (-), or no effect immediately after treatment. Single group studies show effect pre-post treatment; RCT studies show effect compared to (1) active control groups, and (2) inactive control groups. The number of studies with available effect size data is shown in parentheses following study design, and the number of included measures is indicated on each bar.

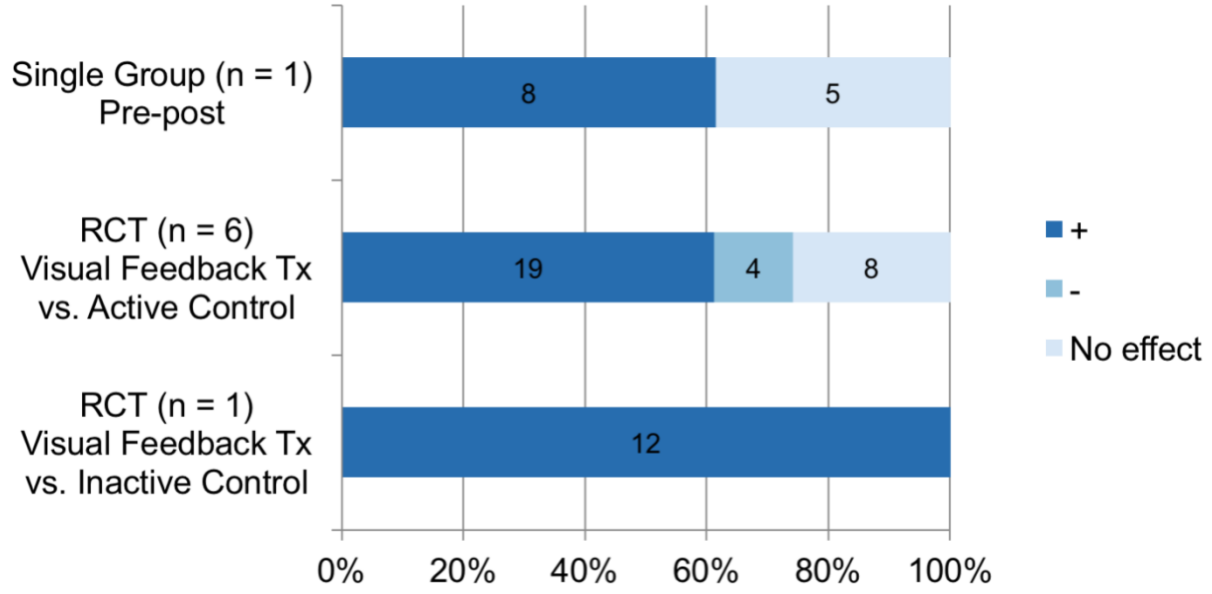

Figure 4. The summary of measures showing positive (+), negative (-), or no effect immediately at follow-up. The measures are grouped by positive (+), negative (-), or no effect. Single group studies show effect pre-treatment to follow-up; RCT studies show effect for visual feedback-based treatment compared to (1) active control groups, and (2) inactive control groups. The number of studies with available effect size data is shown in parentheses following study design, and the number of included measures is indicated on each bar.

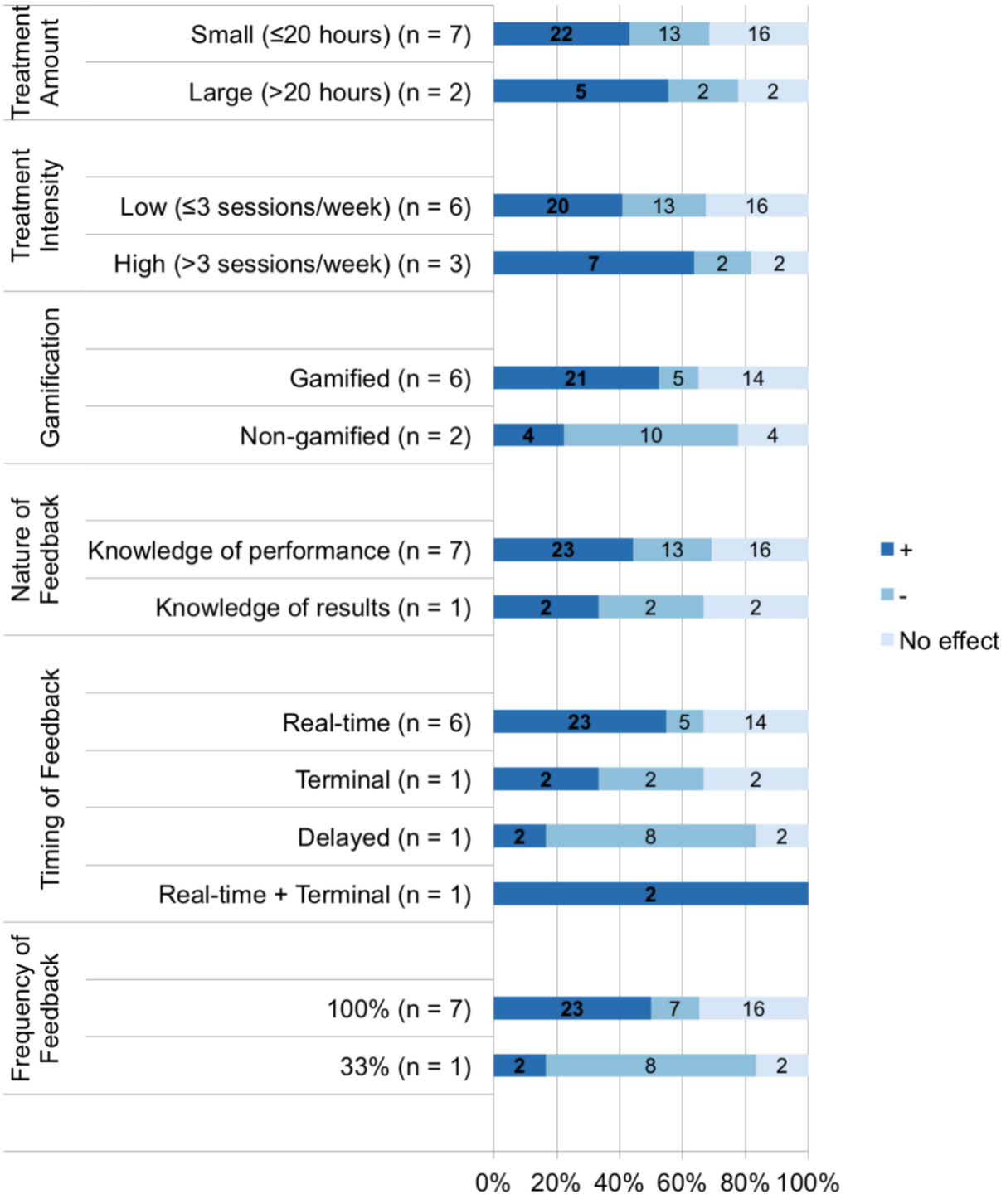

Figure 5. The summary of measures in RCT studies comparing augmented visual feedback-based treatment to active control intervention immediately after treatment. Measures are grouped

by the direction of the effects (positive (+), negative (-), no effect). The number of included measures is indicated on each bar.