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Review

A meta-analysis and systematic literature review of virtual reality rehabilitation programs☆

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A R T I C L E I N F O

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A B S T R A C T

A recent advancement in the study of physical rehabilitation is the application of virtual reality rehabilitation (VRR) programs, in which patients perform practice behaviors while interacting with the computer-simulation of an environment that imitates a physical presence in real or imagined worlds. Despite enthusiasm, much remains unknown about VRR programs. Particularly, two important research questions have been left unanswered: Are VRR programs effective? And, if so, why are VRR programs effective? A meta-analysis is performed in the current article to determine the efficacy of VRR programs, in general, as well as their ability to develop four specific rehabilitation outcomes: motor control, balance, gait, and strength. A systematic literature review is also performed to determine the mechanisms that may cause VRR program success or failure. The results demonstrate that VRR programs are more effective than traditional rehabilitation programs for physical outcome development. Further, three mechanisms have been proposed to cause these improved outcomes: excitement, physical fidelity, and cognitive fidelity; however, empirical research has yet to show that these mechanisms actually prompt better rehabilitation outcomes. The implications of these results and possible avenues for future research and practice are discussed.

Contents

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The modern world is constructed with physically-capable individuals in mind, causing people to be greatly reliant upon their physical abilities. Everyday activities, such as turning doorknobs or climbing stairs, demand certain aspects of bodily functioning. Unfortunately, many neurological disorders and life events can reduce individuals' physical capabilities, among the most widespread being Parkinson's disease (50,000 to 60,000 new cases each year in U.S.; NPF, 2015) and cerebral palsy (10,000 new cases each year in U.S.; CerebralPalsy.org, 2015). People with these conditions often incur great difficulties in performing the aforementioned everyday tasks, resulting in reductions to life satisfaction and well-being (Achten, Visser-Meily, Post, & Schepers, 2012; Gustafsson, Nordström, Stråhle, & Nordström, 2015; Yen et al., 2011). For this reason, researchers have devoted great interest in the rehabilitation of physical abilities through regimented programs.

All physical rehabilitation programs involve the repetition of certain bodily movements, and most utilize certain hardware that can aid or apply resistance to these movements, such as a treadmill or simple weights (Batson et al., 2011; Fung, Richards, Malouin, McFadyen, & Lamontagne, 2006; Mirelman et al., 2010). Recent physical rehabilitation programs, however, have begun applying other devices that present a visual experience to match the repetition of bodily movements. Likely the most widely-used and promising of these new applications is VR — the focus of the current article.

VR is the computer-simulation of an environment that can imitate a physical presence in real or imagined worlds. Often, users control digital recreations of their physical bodies, called avatars, to perform tasks within these virtual environments. To present VR environments, an array of technologies have been applied. Most often, a standard computer monitor is used (Burdea & Coiffet, 2003; Steuer, 1992), but more cutting-edge research has applied surround-screen displays (Cruz-Neira, Sandin, & DeFanti, 1993). To create a surround-screen display, multiple monitors or projectors are placed around the user to provide an encapsulated feeling. Currently, the most cutting-edge VR hardware is the head-mounted display (HMD; Bowman, Kruijff, LaViola, & Poupyrev, 2004; Hinckley & Wigdor, 2002). A HMD is self-contained hardware worn on the head, akin to night-vision goggles, with a digital display that covers the eyes. The wearer's entire field of vision becomes the hardware display, and the HMD tracks head movements to align the visual presentation. Also, users interact with this environment through a keyboard and mouse in typical applications, but more innovative technologies, such as sensor gloves and treadmills, are often used in VR rehabilitation (VRR) programs (Hinckley & Wigdor, 2002). Thus, many technologies can be used to present and interact with a VR environment, allowing for great flexibility in experiences.

Further, VRR programs have been applied to develop four primary outcomes: motor control, balance, gait, and strength. Motor control is the integration of sensory information and application of force to generate a desired movement or action (Holden, Dyar, Schwamm, & Bizzi, 2005; Subramanian, Lourenço, Chilingaryan, Sveistrup, & Levin, 2013). Balance is the control and movement of individuals' center of mass relative to their base of support (Heiden & Lajoie, 2010; Yen et al., 2011). Gait consists of walking-related abilities, which includes the entire process and particular functions (e.g., hip swing and ankle movement; Brütsch et al., 2011; Shema et al., 2014). Lastly, strength is the amount of force able to be generated by oneself. Strength is needed to develop the aforementioned outcomes, but strength can also be developed in isolation (Chen et al., 2012; Deutsch et al., 2002; Lee, 2013).

Despite the application of cutting-edge technologies, extant research on VRR programs has demonstrated varied results, causing researchers and practitioners to remain unsure about the true impact and benefits of VRR programs. Many authors have shown that VRR programs may develop physical outcomes (Cho, Lee, & Song, 2012; Rahman, 2010; Rostami et al., 2011), some even showing that their programs outperform traditional rehabilitation programs (Chen et al., 2012; Ma et al., 2011). On the other hand, other authors have seen lackluster results when testing VRR programs (Kliem & Wiemeyer, 2010; Rose, Brooks, & Attree, 2002; Singh et al., 2012; Yen et al., 2011). Also, differing justifications for the effects of VRR programs have been provided, leaving researchers and practitioners unsure about the mechanisms that may cause VRR programs to be more effective than comparable rehabilitation programs (Brütsch et al., 2011; Shema et al., 2014; Yen et al., 2011). Thus, two important research questions for VRR programs have been left unanswered: Are VRR programs effective? And, if so, why are VRR programs effective?

Due to the importance and centrality of these two questions, the current article provides quantitative and qualitative reviews of VRR programs. For the quantitative review, a meta-analysis is performed to determine the overall efficacy of VRR programs as well as their ability to develop four specific rehabilitation outcomes: motor control, balance, gait, and strength (Bergeron, Lortie, & Guitton, 2015; Chen et al., 2012; Lee, 2013; Yen et al., 2011). Meta-analyses aggregate the statistical results of prior studies to estimate overall effects of interest, and the method is used in the current article to aggregate studies that compare VRR programs against alternative rehabilitation programs. Further, it is important to understand the mechanisms that causes VRR program success or failure; however, it is anticipated that too few authors have empirically studied these mechanisms in controlled studies, disallowing their inclusion in the meta-analysis. For this reason, a systematic literature review is also performed on VRR programs to discover the possible mechanisms that cause VRR program success or failure. Thus, the quantitative review answers the first research question, and the qualitative review answers the second.

By answering these two questions, the current article summarizes the modern state of research and draws several inferences about the future of VRR programs. Primarily, the current article determines whether VRR programs provide benefits beyond traditional rehabilitation programs, indicating whether current practice should refrain from applying these new programs. Equally important, the current article identifies the mechanisms that may cause VRR programs to influence outcomes. Future research and practice can create VRR programs that target these mechanisms, thereby resulting in improved outcomes.

1. Method

Multiple strategies were used to identify all studies, both published and unpublished, that empirically analyze VRR programs. First, searches were conducted in December 2014 in the following scholarly databases: PsycInfo, EBSCOhost, Dissertation Abstracts International, and Google Scholar. Relevant keywords were "virtual reality", "digital simulation", and "computer simulation" (quotations included and searched separately) followed by training, intervention, therapy, enhance, promote, or support. Second, reference sections of relevant meta-analyses and review articles were cross-referenced. Third, emails were sent to selected authors inquiring about any unpublished data. Ninety-eight researchers were contacted, and 31 responses were obtained (32% response rate). Through these efforts a large set of initial sources was identified.

1.1. Inclusion criteria

Initially, 4650 sources were identified, which included articles, dissertations, theses, conference presentations, and unpublished data. Coders were trained on each of the inclusion criteria during weekly meetings, which continued for the entire coding process. The training consisted of discussions of coding decisions and identification of unclear sources. For each inclusion criterion, trained coders independently coded the same set of sources, and interrater agreement was calculated. If the ICC(2, k) value was above 0.8, then the coders began coding separate sources. If the ICC(2, k) value was below 0.8, the coders discussed their decisions until a consensus was reached, and the process was repeated until an ICC(2, k) value of 0.8 was reached.

First, sources must have reported an empirical study to be included in the meta-analysis, resulting in 2784 retained sources. Second, sources must have included (1) quantitative statistics, (2) a sample size larger than nine, and (3) human participants. After removing those that did not qualify, 1954 sources remained. Third, sources must have analyzed the effectiveness of a VR program to alter participant characteristics, resulting in 710 retained sources. Fourth, sources must have included a control group and a post-test, resulting in 292 retained sources. Fifth, sources must have included a VRR program to develop physical outcomes, resulting in 35 retained sources. Last, if a source did not report sufficient information for analyses, the corresponding author was contacted and two follow-up emails were sent. If the author never replied, any outcome that could be included was recorded, but many sources were forced to be excluded. Therefore, 27 sources were included in the final meta-analysis.

To be included in the systematic literature review, sources must have analyzed a VRR program to develop physical outcomes – whether a control group was used or otherwise. Using the above procedures to identify sources, 128 sources were included in the literature review.

1.2. Coding

Two trained coders coded all effect sizes on their outcome category. For instance, if an effect size represented the difference between a VRR program and a comparable program in developing the ability to walk, it was coded as gait. Each effect size was coded as either motor control, balance, gait, or strength. For this process, the two coders independently coded every source and discussed their coding decisions, even after the ICC(2,2) value exceeded 0.80. Disagreements were resolved as a team.

1.3. Statistical analyses

Publication bias, or the "file drawer problem," is a concern for all meta-analyses. Attempts to reduce publication bias were made through several methods, such as contacting researchers for unpublished data, but biases likely exist in the dataset. Funnel plots, fail-safe N, Egger's test, and the trim-and-fill method were used to determine the extent of publication bias. The application of several analyses helps ensure that concerns with a single analysis are addressed by the others, and has been suggested by prior authors (Schmidt & Hunter, 2014).

The heterogeneity of studies was assessed using the I^2 statistic, which is the percentage of variation between studies due to heterogeneity rather than random chance or sampling error. A large I^2 statistic indicates that variation in results is due to study design or sampling bias, and further analyses are warranted. An I^2 value of 25 was chosen as the cutoff for high variation, as suggested by prior authors (Allen, Eby, Poteet, Lentz, & Lima, 2004; Barrick & Mount, 1991; Schmidt & Hunter, 2014).

Results were calculated with Comprehensive Meta-Analysis V3 using a random effects model to calculate standardized mean differences (d), Hedges g, and other included statistics. For all analyses, the standard deviation of change scores were used to standardize results when such data was available, but standard deviations of post-program data were used otherwise. Multiple effect sizes for the same category of outcome in a single study were averaged together. For example, if a study tested a VRR program to develop motor control and three outcome measures were used to gauge effects, these three effect sizes would be averaged together.

2. Results

2.1. Meta-analysis results

2.1.1. Publication bias

Several methods were used to observe bias (Table 1). When analyzing all outcomes together, many studies fell outside the expected range of standard error and effect size (Fig. 1), falling on both sides of the mean effect. Four effect sizes were implied to be missing, but the Egger's test was not statistically significant. These results indicate that slight biases may be present in the overall results, but individual outcomes should also be examined. For individual outcomes, between four and seventeen null results would need to be discovered to substantively alter inferences. Given the notable difficulty in performing VRR studies, these results indicate that the discovered effect sizes are sufficient to obtain an understanding of existing VRR programs. Also, Egger's test was not statistically significant for any outcome, supporting that publication biases were minimized in the meta-analysis. Lastly, the trim-and-fill method with a random effects model indicated that most outcomes did not contain any implied bias. Balance was the only outcome that had implied missing studies, with only one. Therefore, these results support that efforts were successful in reducing publication bias. In agreement with previous meta-analyses, only results calculated with more than three studies are considered reliable.

The I^2 value for most outcomes was above 25, indicating that most observed variability in results was due to true differences and not sampling error. Only strength did not meet this cutoff. Further analyses to determine the cause of variance are warranted for most outcomes.

Table 1
Publication bias analyses results and I^2.

	I^2	Number of Articles	Fail Safe n	Egger's Test β_0	Egger's Test t	Studies Trimmed	
						Left of Mean	Right of Mean
1.) All Outcomes	55.46	27	218	0.54	0.62	4	0
2.) Motor Control	48.60	10	6	0.02	0.01	0	0
3.) Balance	68.32	10	12	0.41	0.15	1	0
4.) Gait	64.40	3	4	4.65	4.52	0	0
5.) Strength	0.00	4	17	−0.08	0.12	0	0

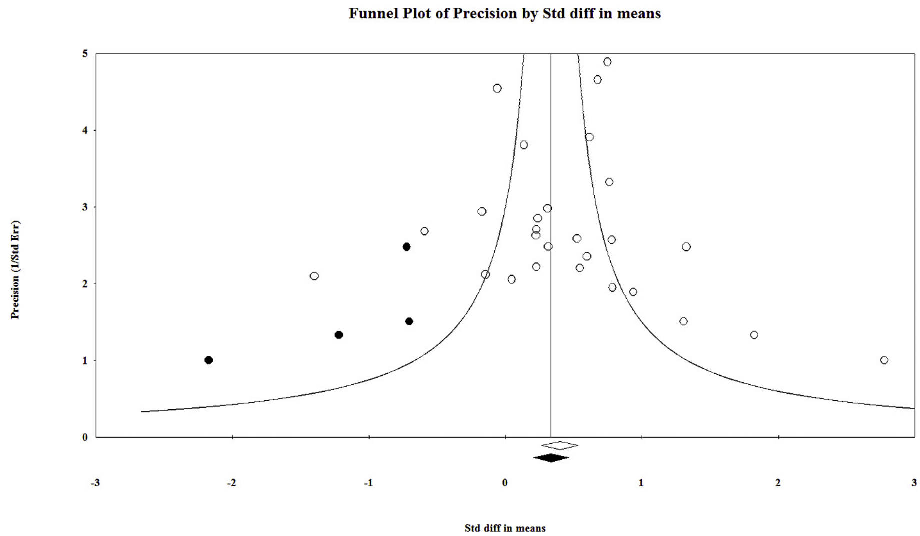

Fig. 1. Funnel plot of publication bias for all outcomes. Note: Observed studies are unfilled circles. Implied missing studies are filled circles.

2.1.2. Main effects

All results are presented as the standard difference of the means (d) between the VRR group and the comparison group. When using this statistic, effects of 0.20 are considered small, effects of 0.50 are considered medium, and effects of 0.80 are considered large (Cohen, 1992). Table 2 presents these effects as calculated by a random effects model. Table 3 also presents these effects as calculated by a random effects model, but only studies are included that explicitly tested VRR programs with physically impaired samples. Some studies tested their programs on other specialized samples, such as those with Down syndrome, and these studies are not included in the calculations provided in Table 3. Lastly, Table 4 likewise applies a random effects model and only includes studies using physically impaired samples, but also restricts the analyses to studies with an alternative treatment group (excluding waitlist designs). Through only including these studies, the true effect of VRR programs beyond comparable alternatives can be determined. Due to the interests at hand, only calculations using physically impaired samples and alternative treatment groups are discussed (Table 4).

Overall, VRR programs are effective. When analyzing all outcomes together, those in VRR programs improved their physical abilities 0.397 standard deviations above comparison groups, and this effect was statistically significant ($p < 0.01$). Amongst the individual outcomes, VRR programs to develop gait abilities demonstrated the largest effects, with an average improvement of 1.041 standard deviation beyond comparison groups; however, great variation can be seen between observed effects, causing this result to only be marginally significant ($p < 0.10$). VRR programs to develop strength also showed a large effect beyond comparison groups, with an average improvement of 0.666 beyond comparison groups. This effect was statistically significant ($p < 0.01$). It should be noted that this effect was calculated with only two studies, and should be interpreted with caution. Nevertheless, when broadening inclusion criteria, this effect remains statistically significant (Table 2, $d = 0.652$, $p < 0.001$; Table 3, $d = 0.633$, $p < 0.001$).

Alternatively, VRR programs to develop motor control abilities and those to develop balance demonstrated smaller effects. VRR programs to develop motor control improved outcomes 0.283 standard deviations beyond comparison groups, and the effect was marginally significant ($p < 0.10$). Lastly, VRR programs to develop balance demonstrated the smallest effects of all, with an average improvement of 0.250 beyond comparison groups. This effect was not statistically significant ($p > 0.10$). Overall, VRR programs are more effective than comparable rehabilitation programs, but variation can be observed across outcomes.

2.2. Systematic literature review results

The systematic literature review identified three mechanisms that were commonly suggested to cause VRR program success or failure, and these mechanisms were seen across research on all outcomes. Although not labeled as such in the literature, the current article labels these mechanisms as: increased excitement, increased physical fidelity, and increased cognitive fidelity. In the following, the systematic literature review is separated by the three mechanisms.

2.2.1. Increased excitement

In typical rehabilitation programs, patients often perceive their experiences as boring and repetitive, especially when the patients are children (Brütsch et al., 2011; Chen et al., 2012; Koenig et al., 2008, pp. 121–126). This should be unsurprising, as many rehabilitation programs prompt patients to perform repeated behaviors

Table 2
Meta-analysis results (random effects model).

Primary Applications	*# of Articles*	*k*	*n*	*d*	*S.E.*	95% Confidence Interval	Hedges *g*	Z-value	*p*
All Outcomes	27	223	1002	0.401	0.107	0.191–0.612	0.392	3.741	<0.001
Motor Control	10	122	442	0.240	0.151	−0.057 to 0.536	0.236	1.586	>0.10
Balance	10	56	275	0.364	0.231	−0.089 to 0.818	0.354	1.575	>0.10
Gait	3	23	56	1.041	0.994	−0.123 to 2.205	0.992	1.753	<0.10
Strength	4	22	229	0.652	0.141	0.376–0.929	0.643	4.623	<0.001

Table 3
Meta-analysis results with only physically impaired samples (random effects model).

Primary Applications	*# of Articles*	*k*	*n*	*d*	*S.E.*	95% Confidence Interval	Hedges *g*	Z-value	*p*
All Outcomes	22	194	640	0.390	0.116	0.162–0.618	0.380	3.353	<0.001
Motor Control	7	101	202	0.275	0.146	−0.012 to 0.562	0.270	1.880	<0.10
Balance	9	55	245	0.250	0.229	−0.198 to 0.699	0.244	1.093	>0.10
Gait	3	23	56	1.041	0.994	−0.123 to 2.205	0.992	1.753	<0.10
Strength	3	15	137	0.633	0.187	0.266–1.000	0.622	3.384	<0.001

Table 4
Meta-analysis results with only physically impaired samples and alternative treatment groups (random effects model).

Primary Applications	*# of Articles*	*k*	*n*	*d*	*S.E.*	95% Confidence Interval	Hedges *g*	Z-value	*p*
All Outcomes	20	170	579	0.397	0.130	0.143–0.651	0.386	3.060	<0.01
Motor Control	6	82	169	0.283	0.161	−0.033 to 0.599	0.277	1.758	<0.10
Balance	9	55	245	0.250	0.229	−0.198 to 0.699	0.244	1.093	>0.10
Gait	3	23	56	1.041	0.994	−0.123 to 2.205	0.992	1.753	<0.10
Strength	2	10	109	0.666	0.214	0.247–1.085	0.657	3.114	<0.01

with little, if any, immediate stimuli and/or results. When patients perceive their experiences as unexciting, they often begin to retract from the programs and become less motivated (Bryanton et al., 2006; Brütsch et al., 2011, 2010). Decreases to motivation may result in less effortful practice of behaviors, thereby resulting in smaller improvements to rehabilitation outcomes (Betker, Desai, Nett, Kapadia, & Szturm, 2007; Mirelman, Bonato, & Deutsch, 2009; Schuler, Brütsch, Müller, Hvan Hedel, & Meyer-Heim, 2011). Even yet, bored patients may even withdraw from rehabilitation programs completely (Walker et al., 2010; Yang et al., 2011; Zimmerli et al., 2012). For this reason, researchers and practitioners have sought methods to create more exciting rehabilitation programs.

To solve this problem, VR has been suggested to add excitement to an otherwise boring rehabilitation program (Merians, Poizner, Boian, Burdea, & Adamovich, 2006; Schuler et al., 2011). Whether exploring a novel world or performing familiar actions, patients naturally consider interactions with a VR environment to be fun and interesting. Likewise, studies have shown that the novelty of immersive displays, such as head-mounted and surround screen displays, causes users to have more positive reactions to their experiences (Bowman et al., 2004; Hinckley & Wigdor, 2002). Even yet, the excitement produced by VR and relevant technologies may be exacerbated if the program includes entertaining game elements, such as challenge or exploration (Bedwell, Pavlas, Heyne, Lazzara, & Salas, 2012; Götz et al., 2011). When patients are excited by their experiences, they are often more motivated to complete them (Bryanton et al., 2006; Brütsch et al., 2011, 2010). Thus, in VRR programs, several factors may cause patients to enjoy their experiences and become more motivated, even when performing otherwise uninteresting behaviors.

To test the effects of VR on excitement and motivation, researchers have developed several VRR programs in which patients complete playful activities (Jang et al., 2005; Merians et al., 2006). For instance, Bryanton et al. (2006) tested a VRR program in which patients use their toes to flick an on-screen coconut, among other game activities. Scores were awarded based on performance, such as the distance flicked, and patients were encouraged to beat their high scores. Patients found the VRR program more exciting and enjoyable than a traditional rehabilitation program, and they exerted more effort during the VRR program compared to a conventional rehabilitation program. Other studies have likewise demonstrated that VRR programs prompt excitement resulting in positive reactions and increased motivation, and these results have been seen across an array of outcome measures (Broeren, Rydmark, & Sunnerhagen, 2004; Merians et al., 2006). Likewise, these benefits to enjoyment and motivation have been observed in studies with sophisticated methodological designs, including longitudinal controlled studies, and across the four primary rehabilitation outcomes: motor control (Jang et al., 2005; Subramanian et al., 2007), balance (Betker et al., 2007; Rendon et al., 2012), gait (Brütsch et al., 2011; Schuler et al., 2011), and strength (Chen et al., 2012; Deutsch et al., 2002; Lee, 2013).

Despite the benefits to excitement and motivation, very few of these studies tested whether increased motivation explicitly causes benefits to rehabilitation outcomes in VRR programs. Often, studies analyze excitement and motivation in isolation, and rehabilitation outcomes are not gauged (Peruzzi, Cereatti, Mirelman, & Della Croce, 2013; Schuler et al., 2011). In other studies, authors test the motivation and outcomes produced by their VRR programs against a control group, but small sample sizes restrict the possibility of analyzing motivation as a mediator of the relationship between programs and outcomes (Adamovich, Fluet, Merians, Mathai, & Qiu, 2008; Lee, 2013; Yang et al., 2011). Further, in many of these studies, the comparison group does not receive a comparable treatment that is matched for duration and/or intensity (Cho et al., 2012; Kwon, Park, Yoon, & Park, 2011). Often, the comparison group receives a standard rehabilitation program, whereas the VRR group receives the standard program along with the VRR program (Thielbar et al., 2014; Yin, Sien, Ying, Chung, & Leng, 2014). These methodological concerns make it unclear whether the increases to motivation caused by VR actually provides subsequent improvements to outcomes beyond typical rehabilitation programs, even when studies use methodological designs that may permit such analyses.

Further, these criticisms are prevalent no matter the outcome studied, but they are exemplified in VRR research using the Nintendo Wii to improve balance. Cho et al. (2012) and Rahman (2010) demonstrated that a VR balance program via the Wii in addition to a typical balance program provided greater improvements to patients' balance compared to those who only received the typical balance program. Rendon et al. (2012) demonstrated that a VR balance program via the Wii significantly improved elderly patients' balance compared to a group that received no program at all. The authors of these studies argued that improvements were prompted by the added enjoyment and motivation provided by the Wii; however, analyses did not permit these claims, and their results may simply be due to the added benefit of additional exercise altogether. This argument is supplemented by Singh et al. (2012; 2013) who discovered that a VR balance program via the Wii was equally effective as a traditional balance program when matched for total duration. Therefore, despite the often discussed benefit of increased enjoyment and motivation in VRR programs, firm evidence does not exist to support this mechanism as the cause of VRR program success.

Together, these studies provide several inferences. Notably, patients often perceive VRR programs as more enjoyable than comparable rehabilitation programs, resulting in benefits to motivation. Authors have yet to show, however, that this increased motivation explicitly causes VRR programs to provide improved rehabilitation outcomes beyond comparable rehabilitation programs. While no more research is needed to demonstrate that VRR programs prompt enjoyment and motivation, future research is certainly needed to empirically show that enjoyment and motivation are the mediating mechanisms between VRR programs and rehabilitation outcomes. Therefore, while much has been demonstrated about enjoyment and motivation in VRR programs, much is also yet to be discovered.

2.2.2. Increased physical fidelity

Often, patients in typical rehabilitation programs develop abilities through performing practice behaviors that are dissimilar to typical activities (Holden & Dyar, 2002; Holden et al., 2005; Subramanian et al., 2013). For instance, to developing motor control, patients in traditional rehabilitation programs often perform abstract behaviors, such as moving their hand in a circle or performing finger tapping exercises, instead of performing more typical motor control activities, such as writing with a pencil or manipulating objects in a natural manner (Broeren et al., 2004; Jang et al., 2005; Merians et al., 2006). Likewise, to develop gait, patients may be asked to perform certain knee or ankle movements instead of walking (Mirelman et al., 2010; Shema et al., 2014). Typically, behaviors such as these are performed to develop specific muscles or particular aspects of desired abilities. Sometimes, these behaviors are performed when patients cannot perform the more complex or difficult activities. Many authors, however, have questioned the ability of dissimilar practice behaviors to develop rehabilitation outcomes.

These authors argue for the importance of “learning by imitation,” whereby rehabilitation programs can be more beneficial when patients perform practice behaviors that imitate desired transfer tasks (Holden et al., 2005). Performing the actual activities of interest provides the relevant cues that are needed to learn the desired activity (Mirelman et al., 2010; Shema et al., 2014). For instance, individuals alter their walking patterns when they traverse sloped surfaces, and the visual appearance of a slope subconsciously prompts these altered walking patterns. Without these visual cues, patients may struggle to develop their gait abilities, and the same is true for almost all other rehabilitation outcomes. Thus, cues are likely needed in rehabilitation programs to truly develop the abilities of interest and improve outcomes, which can only be provided through performing realistic practice behaviors.

Further, in typical rehabilitation programs, patients may need to “translate” their learned physical abilities to more naturalistic applications (Holden & Dyar, 2002; Holden et al., 2005; Subramanian et al., 2013). Only performing certain aspects of the abilities of interest may not sufficiently develop all necessary muscles, and patients may not develop the skill to sequentially link together the different aspects of the abilities. While patients may be able to lift their arm, maneuver their fingers, and rotate their wrist, they may not be able to do each of these activities sequentially to write with a pencil. Therefore, many authors propose that the practice behaviors performed in rehabilitation programs should be as similar to abilities of interest in order to improve outcomes.

Also, rehabilitation tasks that are similar to desired activities may activate relevant neurological pathways, and this activation may prompt cognitive rehabilitation benefits as well as physical (Bermudez i Badia, Garcia Morgade, Samaha, & Verschure, 2013; Jang et al., 2005; Lucca, 2009). Many physical impairments are due to neurological dysfunction, such as stroke, and physical abilities cannot be regained without proper cognitive functioning. Through activating neurological pathways, relevant aspects of cognitive functioning can be strengthened, which may likewise develop physical outcomes. Thus, the ability to develop neurological pathways is especially important for rehabilitation efforts, which may be achieved through realistic programs.

Fortunately, VRR programs may be a solution to these concerns. Modern technologies can present any scenario in a VR environment, allowing patients undergoing a VRR program to develop outcomes by performing similar, if not exact, behaviors as the abilities of interest. For instance, Holden and Dyar (2002) created a VRR motor control program where patients perform everyday activities in a digital environment, such as placing an envelope in a mail slot. Likewise, You et al. (2005) tested a VRR gait program in which patients interacted with a realistic environment while walking and climbing steps. In both investigations and others (Mirelman et al., 2010; Peruzzi et al., 2013; Shema et al., 2014), patients enjoy their realistic experiences and adequately develop their physical abilities. Further, Lucca (2009) and Bermudez i Badia et al. (2013) even demonstrated that relevant neurological pathways are active during and after a VRR program with realistic practice behaviors.

Extant research, however, has provided very little evidence that physical fidelity actually improves rehabilitation outcomes. Authors have shown that VRR programs that present realistic scenarios and prompt realistic practice behaviors can improve rehabilitation outcomes (Holden & Dyar, 2002; Holden et al., 2005; Subramanian et al., 2013), but research has yet to show that physical fidelity is the exact cause of success for these programs. Instead, the chosen combination of practice behaviors may have caused the improvements to outcomes, instead of any aspect of the VRR program itself. Likewise, while similar VRR tasks activate neurological pathways, extant research is unable to conclude that this mechanism actually prompts the observed outcomes in VRR programs (Bermudez i Badia et al., 2013; Lucca, 2009; You et al., 2005).

A possible reason that research has yet to support the benefits of physical fidelity may be the difficulty to study. Physical fidelity is a property of an entire VRR program. To determine whether physical fidelity causes improved rehabilitation outcomes, researchers must compare several VRR programs. Currently, VRR programs are expensive, and most researchers do not have the resources to compare multiple VRR programs. Therefore, while many authors claim that physical fidelity is the cause of VRR success, extant research has not supported this notion.

Research on physical fidelity in VRR programs can provide several inferences. Many authors have suggested that physical fidelity leads to noteworthy benefits. Particularly, physical fidelity eliminates the need to “translate” practiced behaviors, strengthens relevant muscles, develops the ability to sequentially link together multiple actions, and activates relevant neurological pathways. Despite these suggestions, research has yet to provide evidence that physical fidelity or these benefits actually causes improved rehabilitation outcomes – a clearly important research question for future investigations. Therefore, while physical fidelity is often considered a great benefit of VRR programs, extant research has yet to support this notion.

2.2.3. Increased cognitive fidelity

When undergoing a traditional rehabilitation program, patients often perform practice behaviors in a relatively stimulus-free environment (Mirelman et al., 2010; Peruzzi et al., 2013; Shema et al., 2014). When performing these behaviors outside of a clinical environment, however, many cognitive demands may be present. When walking, for example, people are expected to hold conversations and allocate attention to other activities. Authors have suggested that cognitive fidelity, which is the extent that a program prompts similar psychological processes as the transfer environment, is an important components of a successful rehabilitation program. When performing practice behaviors in a clinical environment with minimal cognitive fidelity, patients may experience difficulty when performing these behaviors outside of the clinical environment, as patients may be unprepared for the additional cognitive demands and/or perceived stress (Heiden & Lajoie, 2010; Yen et al., 2011).

Researchers have applied several methods to increase cognitive fidelity in a typical rehabilitation program. Often, patients are asked to perform practice behaviors while holding an irrelevant conversation or completing verbal math problems, and patients find these programs more cognitively demanding and stressful (Peruzzi et al., 2013; Shema et al., 2014). While success has been seen with these methods, authors have suggested that further success can be achieved with even more realistic cognitive demands.

VR can present an array of scenarios that demand cognitive attention, preventing patients from devoting their full attention to practice behaviors (Heiden & Lajoie, 2010; Yen et al., 2011), and authors have already created VRR programs for this exact purpose. In regards to balance, Heiden and Lajoie (2010) tested a VR balance program in which patients stood on two pressure sensors that recorded their center of pressure (COP) to control a video game. Patients who underwent this rehabilitation program in addition to a typical balance rehabilitation program did not show greater improvements in balance or gait compared to those that only underwent a typical balance rehabilitation program; however, they improved in their ability to respond to an unexpected auditory stimulus. Similarly, Yen et al. (2011) demonstrated that a VR balance program, which patients used a balance board to control interactive games, was equally effective as a traditional balance program in developing patients' balance, and no significant changes were observed in either group for dual-task performance.

Also, several authors have likewise tested VRR programs with heightened cognitive fidelity for gait development. Mirelman et al. (2010) compared a VRR program against a typical treadmill program. In the VRR, participants were required to, "make decisions about obstacle negotiation in two planes, while continuing to walk on the treadmill. These decisions were made more difficult with distracters, such as changes in lighting and moving objects" (Mirelman et al., 2010, p. 2). The VRR program was more effective in developing dual-task walking speed and stride length, but both programs were equally effective in developing usual walking speed. Shema et al. (2014) employed a similar program to develop dual-task gait activities and object negation. Patients experienced improved mobility and decreased risk of falls, but no comparison group was used for any analyses.

These results provide several noteworthy inferences. VRR programs with increased cognitive fidelity may improve dual-task performance, but, in their current form, they do not provide greater benefits than traditional programs in developing rehabilitation outcomes. With improved technologies, however, future research may demonstrate that these VRR programs may become superior in developing rehabilitation outcomes. Further, like the other two proposed mediating mechanisms, authors have yet to empirically demonstrate that cognitive fidelity is the cause of any observed outcomes. When testing the effects of cognitive fidelity in future research, researchers should consider whether the tested VRR programs actually provide improved cognitive fidelity instead of simply greater cognitive demands. While either may improve outcomes, research cannot effectively progress if constructs are mislabeled across studies. Therefore, much is yet to be discovered about cognitive fidelity in VRR programs, including whether the mediating mechanism has an effect at all.

3. Discussion

The goal of the current article was to answer two important research questions for the future of VRR programs. The first was: Are VRR programs effective? The meta-analysis revealed that VRR programs are, overall, more effective than comparable rehabilitation programs, demonstrating a significant and moderate effect. Also, variations were observed across specific outcomes. VRR programs are apt for developing strength and gait. For strength, the observed effect was large and statistically significant, but notable variation was observed in results for gait. While the respective effect was extremely large and positive, it was only marginally significant, posing some doubt towards the true efficacy of VRR programs for gait development. Similarly, VRR programs were more effective than alternatives for developing motor control and balance, but the effects were small. The effect for motor control was marginally significant. In the case of balance, the effect was not significant.

Together, these results are promising for the effectiveness of VRR programs. The study of VRR programs is still in its infancy. Although some results may seem lackluster, authors have had very little time to optimize their VRR programs. Despite this fact, VRR programs were more effective, on average, than alternative programs for all outcomes, both when analyzed together and separately. In other words, no observed effect was in a negative direction, and VRR programs are a promising rehabilitation method. Therefore, the answer to the first research question of the current article – Are VRR programs effective? – would be yes.

The second research question in the current article was: Why are VRR programs effective? From these systematic literature review, three mediating mechanisms have been proposed to explain VRR success. These are increased excitement, physical fidelity, and cognitive fidelity. Despite the popularity of attributing VRR program success to these mediating mechanisms, firm evidence has yet to support their relationship to outcomes. With these results in mind, implications for research and practice should be considered.

Although recently developed, VRR programs have already found their place in rehabilitation research and practice. Only a few years ago, authors still appeared unsure about the possibility of VRR programs providing benefits beyond traditional rehabilitation programs (Holden & Dyar, 2002; Holden et al., 2005; Subramanian et al., 2013). Now, it should be clear that VRR programs are able to provide benefits, even beyond traditional rehabilitation programs; however, it is still unclear whether the costs of VRR programs are less than the benefits, and a cost-benefits analysis should be conducted before applying the novel technology.

Further, research has provided theoretical perspectives to understand VRR programs, although specific theories are rarely applied in the current literature. In regards to the first possible mediating mechanism discussed, excitement, the actual impact of excitement is believed to be through improvements to motivation (Brütsch et al., 2011; Chen et al., 2012; Koenig et al., 2008, pp. 121–126). Thereby, many theories of motivation can be applied to predict the effects of VRR programs (Locke & Latham, 2002; Steel & König, 2006; Steers, Mowday, & Shapiro, 2004). Particularly, VRR programs may specifically prompt intrinsic motivation, especially if game elements are included (Bedwell et al., 2012; Bryanton et al., 2006; Götz et al., 2011). Users naturally find interactions with VRR programs as gratifying, whereas typical rehabilitation programs may provide unclear rewards – if any at all. Currently, the most commonly applied theory to understand the dynamics of intrinsic motivation (as well as extrinsic motivation) is self-determination theory (SDT; Deci & Ryan, 2002; Gagné & Deci, 2005; Ryan & Deci, 2000). Several avenues for future research should be considered through applying SDT.

Likewise, much is already known about the dynamics of physical and cognitive fidelity. Most of this research is studied in the context of organizational training programs (Beidas, Cross, & Dorsey, 2014; Hays & Singer, 2012). Most often, these programs focus on developing cognitive abilities, such as declarative knowledge and skills. Nevertheless, this area of research has discovered many theoretical approaches to study fidelity that could be applied to VRR programs, such as analyzing the differences between skill acquisition and skill application. These avenues for future research should be explored through applying prior findings to VRR programs.

3.1. Future directions

Two extremely popular research questions for the study of VRR programs should no longer be investigated. While VRR programs are continuously created and tested, it is no longer novel or important to demonstrate that a VRR program can provide rehabilitation benefits. Studies without comparison groups, or even those with waitlist control groups, provide little information to further our understanding of VRR programs. In the current literature, even studies with alternative treatment groups, especially those with small sample sizes, struggle to provide novel findings when only investigating rehabilitation outcomes, and other relationships should be investigated in future research and practice. Likewise, authors have repeatedly demonstrated that patients enjoy VRR programs more so than traditional VRR programs. Once again, it is no longer novel or useful to show this finding with additional VRR programs.

Fortunately, several future directions for research can be identified from the current article. Despite a three proposed possibilities, the mechanisms that prompt VRR programs to provide greater rehabilitation outcomes are largely unknown, as authors have yet to demonstrate a consistent mediating effects of any variable between VRR programs and rehabilitation outcomes. Of most importance, authors often show that VR elicits patient enjoyment and motivation, but it is still unknown whether these mechanisms actually cause improved benefits for VRR programs. Future research should empirically demonstrate the commonly assumed cause of VRR program success. In doing so, many theories of motivation (Locke & Latham, 2002; Steel & König, 2006; Steers et al., 2004) should be applied to make specific predictions about the effect of excitement and enjoyment in VRR programs. Possibly the most relevant motivation theory is SDT (Deci & Ryan, 2002; Gagné & Deci, 2005; Ryan & Deci, 2000).

SDT proposes that certain types of motivation lead to particular outcomes (Deci & Ryan, 2011, 2012; Ng et al., 2012; Teixeira, Carraça, Markland, Silva, & Ryan, 2012). Originally, the theory differentiated intrinsic and extrinsic motivation, but it has since been revised to differentiate autonomous and controlled motivation. The former, autonomous motivation, refers to intrinsic motivation and well-internalized extrinsic motivation. The latter, controlled motivation, refers to extrinsic motivation arising from rewards, punishments, and introjected regulation (i.e. approval, shame, self-esteem). Research has shown that completing tasks while having a controlled motivation depletes energy and other possible resources. On the other hand, completing tasks while having an autonomous motivation is not depleting, but may even enhance energy. Thus, when completing tasks, such as practice rehabilitation behaviors, it is beneficial to prompt autonomous motivation rather than controlled motivation, but either type of motivation is better than no motivation at all.

When applying SDT to VRR programs, three noteworthy research questions may be important. First: do VRR programs prompt autonomous or controlled motivation? Certain aspects of VRR programs appear to relate to autonomous motivation. Patients naturally enjoy their experiences in VR environments, and they are often intrinsically motivated to perform practice behaviors (Brütsch et al., 2011; Chen et al., 2012; Koenig et al., 2008, pp. 121–126). Nevertheless, certain aspects also appear to relate to controlled motivation. Particularly, many VRR programs include the game element of score (Bedwell et al., 2012; Götz et al., 2011). Score represents an external reward for performing a certain behavior, thereby prompting controlled motivation. Given that prior research has heavily supported the benefits of autonomous motivation beyond controlled motivation, future research should determine whether VRR programs prompt autonomous motivation, controlled motivation, or both. Similarly, future research should determine the specific aspects of VRR programs that prompt these types of motivation.

Second: does prompting motivation to use a VRR program result in the same outcomes as prompting motivation to achieve rehabilitation outcomes? When applying SDT, authors have repeatedly noted that the target of motivation greatly impacts outcomes (Deci & Ryan, 2002; Gagné & Deci, 2005). If patients are only motivated to use the VRR program, rather to achieve rehabilitation outcomes in general, they may be less likely to perform practice behaviors outside the program. Alternatively, if patients are motivated to achieve rehabilitation outcomes, they may be likely to use the VRR program and perform practice behaviors outside the program. Future research should consider the methods that different targets of motivation may improve outcomes from VRR programs.

Third: does the motivation caused by a VRR program differ from a typical rehabilitation program? As discovered in the systematic literature review, VRR and typical rehabilitation programs differ in the amount of motivation that they prompt. It is possible that the observed differences in the two programs are not due to the amount of motivation caused, but rather the type of motivation caused. Particularly, VRR programs may prompt autonomous motivation whereas typical rehabilitation programs may prompt controlled motivation, causing the observed differences in outcomes. Together, these three research questions are pivotal for the understanding of VRR programs and motivation, a popularly cited cause of program success, but these questions also represent the tip of the iceberg for the application of SDT. Future research should explore these questions as well as many more.

In addition to motivation, physical and cognitive fidelity have been suggested to provide benefits to VRR program outcomes. The current article strongly urges researchers to analyze the activated neurological pathways involved within VRR programs and traditional rehabilitation programs. As mentioned, several conditions that prompt the need for rehabilitation stem from neurological deficiencies (Bermudez i Badia et al., 2013; Lucca, 2009). It is logical that rehabilitation programs for these conditions should prompt cognitive as well as physical benefits to obtain maximum effectiveness. If future research can conclusively demonstrate this link, researchers can further identify the exact neurological pathways that lead to rehabilitation success, and create VRR programs that activate relevant neurological pathways to improve outcomes. This research question may be the most important for the future of VRR programs.

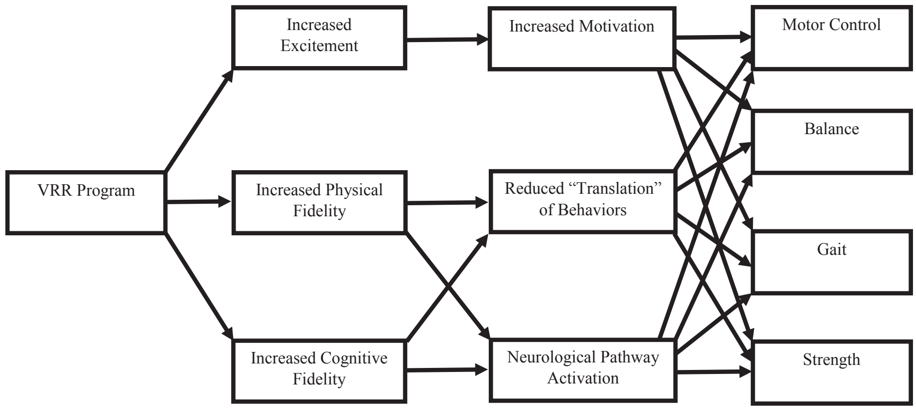

Fig. 2. Proposed mechanisms of VRR program success.

Beyond the activation of neurological pathways, relevant theoretical perspectives should also be applied to understand the possible effects of physical and cognitive fidelity. As many studies have shown, skill acquisition is different than skill application. Authors have suggested that both, high and low fidelity programs may develop skill acquisition, but only high fidelity programs may develop skill application (Beidas et al., 2014; Hays & Singer, 2012). Future research should test whether this notion is true for VRR programs. Also, in all tests of VRR programs, researchers should remain cognizant of the differences between measuring success through skill acquisition and measuring success through skill application. The latter is more indicative of physical development, but it is certainly harder to successfully measure. Kirkpatrick's (1967, 1979) training evaluation model may be helpful for future research to conceptualize the different types of rehabilitation outcomes, and related research on this model can provide information about gauging the specific outcomes of interest (Alliger & Janak, 1989).

Further, in many other applications of VR, authors have examined the importance of perceived realism on immersion and presence as well as the subsequent outcomes caused by these feelings (Botella et al., 2013; Hoffman et al., 2011). These other applications, such as organizational training and clinical therapy, largely involve the development of cognitive outcomes. Given that immersion and presence are cognitive in nature, it is unsurprising that these areas would demonstrate an interest. Although VRR programs involve physical outcomes, immersion and presence may still have an effect on physical rehabilitation outcomes, even if through the mediator of motivation or neurological pathway activation.

Lastly, many recurrent methodological concerns arose in studies on VRR programs. First, most studies contain small sample sizes, and many are single-case studies. While these small studies can provide important initial inferences about a topic, they can provide few, if any, firm conclusions. Future research should move beyond these limited methodological designs.

Second, although the meta-analysis only analyzed studies that included alternative treatment groups for comparisons, such sophisticated methodologies are not regularly applied. Many studies conduct analyses that are not based on group comparisons, but instead focus on pre- and post-treatment differences within the VRR program group. Even when studies contain control groups, they often undergo no rehabilitation program at all. The use of no or unequal control groups poses concerns. In these cases, it is unclear whether VRR programs, specifically, provide beneficial rehabilitation outcomes, or whether any program would produce similar outcomes. Future research should strive towards applying research designs that utilize alternative treatment groups to avoid these concerns.

Third, across each application, little agreement can be seen in standardized outcome measures. In Moreira, de Amorim Lima, Ferraz, and Benedetti Rodrigues (2013) review of VRR programs to develop gait, the authors note that no study included the same outcome measures. Authors may be applying measures with poor validity or reliability, which may obfuscate the actual impact of VRR programs. Future research should apply standardized measures, when possible.

4. Conclusion

Together, the meta-analysis and systematic literature review provide several inferences for current and future research and practice. While VRR programs are relatively new, these programs are already more effective than traditional rehabilitation programs. The answer to the question – Are VRR programs effective? – is yes. Alternatively, much is still unknown about the mediating mechanism that prompt VRR success. Three mechanisms have been proposed in the literature: enjoyment, physical fidelity, and cognitive fidelity. Authors have shown that VRR prompts enjoyment and motivation, but these two factors have yet to be shown as the cause of improved outcomes. Likewise, few outcomes of physical and cognitive fidelity have been empirically demonstrated. The answer to the question – why are VRR programs effective? – is still unknown, although some possible solutions have been suggested. Fig. 2 provides a visual summary of these proposed mediating mechanisms to guide future research and practice, and SDT was suggested to be effective in determining the cause of VR success. Together, the current applications of VRR are promising, and several avenues for future research and practice will likely further develop these programs to provide even greater outcomes.

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