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## The design and evaluation of biofeedback in motor therapy gaming

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Manuscript ID	Draft
Manuscript Type:	Original Design Article
Keywords:	Assessment, Developmental Disability, Knowledge Translation, Neurorehabilitation and Brain Computer Interfaces, Pediatrics, Recreation, Usability
Abstract:	<p>This article details the design of a co-created, evidence-based biofeedback therapy game addressing the research question: is the biofeedback implementation efficient, effective, and engaging for promoting quality movement during a therapy game focused on hand gestures?</p> <p>First, we engaged nine young people with Cerebral Palsy (CP) as design partners to co-create the biofeedback implementation. A commercially available, tap-controlled game was converted into a gesture-controlled game with added biofeedback. The game is controlled by forearm electromyography and inertial sensors. Changes required to integrate biofeedback are described in detail and highlight the importance of closely linking movement quality to short- and long-term game rewards.</p> <p>After development, 19 participants (8-17 years old) with CP played the game at home for four-weeks. Participants played 17±9 minutes/day, 4±1 days/week. The biofeedback implementation proved efficient (i.e. participants reduced compensatory arm movements by 10.2±4.0%), effective (i.e. participants made higher quality gestures over time) and engaging (i.e. participants consistently chose to review biofeedback). Participants found the game usable and enjoyable.</p> <p>Biofeedback design in therapy games should consider principles of motor learning, best practices in video game design, and user perspectives. Design recommendations for integrating biofeedback into therapy games are compiled in an infographic to support interdisciplinary knowledge sharing.</p>

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## The design and evaluation of biofeedback in motor therapy gaming

This article details the design of a co-created, evidence-based biofeedback therapy game addressing the research question: is the biofeedback implementation efficient, effective, and engaging for promoting quality movement during a therapy game focused on hand gestures?

First, we engaged nine young people with Cerebral Palsy (CP) as design partners to co-create the biofeedback implementation. A commercially available, tap-controlled game was converted into a gesture-controlled game with added biofeedback. The game is controlled by forearm electromyography and inertial sensors. Changes required to integrate biofeedback are described in detail and highlight the importance of closely linking movement quality to short- and long-term game rewards.

After development, 19 participants (8-17 years old) with CP played the game at home for four-weeks. Participants played  $17\pm 9$  minutes/day,  $4\pm 1$  days/week. The biofeedback implementation proved efficient (i.e. participants reduced compensatory arm movements by  $10.2\pm 4.0\%$ ), effective (i.e. participants made higher quality gestures over time) and engaging (i.e. participants consistently chose to review biofeedback). Participants found the game usable and enjoyable.

Biofeedback design in therapy games should consider principles of motor learning, best practices in video game design, and user perspectives. Design recommendations for integrating biofeedback into therapy games are compiled in an infographic to support interdisciplinary knowledge sharing.

Keywords: assessment; developmental disability; knowledge translation; neurorehabilitation and brain computer interfaces; pediatrics; recreation; usability; biofeedback

## Introduction

Cerebral palsy (CP) is a disability due to brain injury or abnormality near birth and persists through the lifespan (Rosenbaum et al., 2007). CP can impact a person's motor control, perception, intellectual function, ability to perform daily activities and participate in society (Novak et al., 2013). Persons with CP can have impaired hand or arm function affecting motor activities. Improving performance in motor activities requires frequent and intense practice (MacIntosh, Lam, Vigneron, Vignais, & Biddiss, 2018). Understandably, much research has focused on designing engaging activities to promote practice and improve function. Integrating technologies and games into rehabilitation therapies is an approach of great interest to children, their families and clinicians (Howcroft et al., 2012). Previous work has explored the use of entertainment gaming systems such as the Nintendo Wii and Sony EyeToy as well as custom-designed therapy systems for motor rehabilitation with varying success (Kanitkar et al., 2017). One limitation of many technologies used to promote engaging practice of therapy activities is the poor quality or lack of feedback provided by the system to inform task performance (James, Ziviani, Ware, & Boyd, 2015). In previous studies, young people with CP and their families have reported a desire for more accurate feedback that can inform both real-time performance (i.e. "am I doing the movement right?") and progress over time (i.e. "are my abilities changing?") (James, Ziviani, King, & Boyd, 2015).

Feedback impacts how well tasks are learned, a person's focus and their motivation (Wulf, Shea, & Lewthwaite, 2010). Biofeedback, where a person receives information about their body state (e.g. heart rate, foot speed, muscle activity), can help increase awareness and control by informing the individual to how their body is functioning (Timmermans, Seelen, Willmann, & Kingma, 2009; van Dijk, Jannink, & Hermens, 2005). Biofeedback in motor activities can be used to provide (i) "*knowledge*

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3 *of performance*” (KP) indicating the quality of a movement (e.g., compensatory  
4 movements performed while throwing a ball) as well as (ii) “*knowledge of results*”  
5 (KR) indicating how successful an action was with respect to the desired outcome (e.g.,  
6 whether the ball hit a target). An evidence-based biofeedback strategy: a) offers  
7 autonomy, making people active contributors to their practice by building a sense of  
8 ownership (Taylor, Dodd, McBurney, & Graham, 2004), b) is proportionate to the  
9 person’s ability, and c) varies in presentation (e.g. visual, audio) (Biddiss, Chan-Viquez,  
10 Cheung, & King, 2019; MacIntosh et al., 2018). These attributes fuel a person’s interest  
11 in their own performance and helps them refine their movements ultimately enhancing  
12 motivation, independence and self-efficacy (MacIntosh et al., 2018; Wulf, 2006).  
13 However, a recent review found that biofeedback strategies used in motor interventions  
14 for people with CP are rarely based on motor learning principles or clinical evidence  
15 (MacIntosh et al., 2018). Traditionally, biofeedback has been given in a way that may  
16 slow motor learning by forcing the person into a passive role in their practice, building  
17 dependence on the feedback (Timmermans et al., 2009). Improving the quality of  
18 biofeedback in therapy games may positively impact functional outcomes by increasing  
19 engagement and efficiency of home-based practice (Howcroft et al., 2012).

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This article describes the design and evaluation of a biofeedback therapy game  
for home-based motor rehabilitation. Note, this paper does not aim to describe clinical  
effectiveness, but rather to assess how the biofeedback implementation helps  
participants take interest in their practice and adjust their motor activities at home. The  
project was conducted in two phases. In phase 1, we engaged with young people with  
CP, clinicians, and a video game developer through a participatory design approach to  
answer the research question: *how can user-centred biofeedback be integrated in an  
existing commercial video game to promote motor learning?* In phase 2, the

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3 biofeedback implementation is evaluated in-home for four weeks by 19 young people  
4 with CP to answer the question: *is the co-created biofeedback implementation (i)*  
5 *efficient, (ii) effective, and (iii) engaging from the perspective of its users for promoting*  
6 *quality movement during a therapy game focused on hand gestures?* Specifically, we  
7 expect that participants will: i) adapt their movements immediately after KP  
8 biofeedback is presented informing on movement quality (*efficient*), ii) improve  
9 performance in the task over time (*effective*), iii) choose to review KR biofeedback  
10 informing on task performance when presented the opportunity (*engaging*).  
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## 23 **Methods**

### 24 ***Phase 1: Design approach***

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26 In line with the framework presented by (Druin, 2002), we recruited young people with  
27 CP (10-23 years old, with mild-moderately impaired use of one hand, Manual Abilities  
28 Classification System (MACS) level I-III (Eliasson et al., 2006) to participate as ‘design  
29 partners’ to integrate evidence-based biofeedback principles into a commercial video  
30 game. As design partners, participants were consulted throughout the process from  
31 ideation to final product (Druin, 2002). Participants tested game prototypes during 1-  
32 hour, one-on-one, sessions with a researcher. Three occupational therapists were also  
33 consulted and attended design sessions when required by participants. Biofeedback  
34 elements were added to the game and refined at each session. Researchers prompted  
35 participants to verbalize their thoughts related to biofeedback timing, aesthetic design,  
36 comprehension, and motivation during and after play-testing. Sessions were completed  
37 in an urban North American centre and a rural Western European centre to build  
38 biofeedback presentation receptive across cultures. After each design session,  
39 participant responses were synthesized, and changes were made to the game for the next  
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3 session. These changes were recorded in an audit trail to keep track of the decisions  
4 made and rationale. After the end of the design phase, the therapy video game with  
5 integrated biofeedback was ready for testing in-home.  
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### 10 11 *Gaming system description*

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14 Biofeedback was added to the commercial game, 'Dashy Square' (KasSanity Inc.). The  
15 game objective is to navigate through 10 levels of increasing difficulty without touching  
16 obstacles. Example gameplay can be seen [here](#). In the game's original form, players  
17 press a key to evade obstacles. Working with the developer, controls were changed from  
18 a single key press to a gesture-based controller using electromyography (EMG) and  
19 inertial sensors detected with the Myo Armband (Thalmic Labs). Participants wore the  
20 Myo Armband on the forearm of their affected side. Raw data from the armband's  
21 eight-channel EMG and 9-axis inertial measurement unit (IMU)) were processed  
22 through custom scripts developed in MATLAB 2017b to interpret gestures and  
23 command the game. Development of the classification algorithms for detecting these  
24 gestures will be described in a parallel paper, *in prep.* (MacIntosh, Biddiss, Vignais, &  
25 Vigneron, 2019). Participants and therapists were consulted to determine the desired  
26 gesture with which to control the game. Gestures were one of: wrist extension- active  
27 fingers, wrist extension- relaxed fingers, finger-thumb pinch, supination. The  
28 biofeedback was designed to reward completion of the therapeutic goals identified by  
29 clinicians and participants: making the gesture at the correct time and having high  
30 quality movement (i.e. low co-contraction and fewer compensatory movements).  
31 Specifically, co-contraction was quantified as the ratio between extensor and flexor  
32 muscle activity. High forearm extensor activity while keeping flexor activity low was  
33 associated with less co-contraction and higher quality movement. Compensatory arm  
34 movements were detected by the IMU. Fewer arm movements, quantified by the  
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3 resultant angular velocity variability of the forearm, were associated with more isolated  
4 hand movements and higher quality movement. During design sessions, participants  
5 tested the custom gesture-controlled version of Dashy Square with added biofeedback  
6 elements. In summary, the biofeedback elements added to the game because of the co-  
7 design process were (full details in Results, Table 1):  
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15 (1) *Dodge points* given for avoiding obstacles, linked to correct timing of a gesture.
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17 (2) *Style points* were linked to quality of movement, specifically the extent of co-  
18 contraction. Higher 'Style Points' means greater extensor and lesser flexor  
19 activity (less co-contraction).  
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- 24 (3) *Speed-change* biofeedback events were linked to quality of movement,  
25 specifically the extent of compensatory arm movements. When compensatory  
26 arm movements were detected beyond an individualized threshold, game speed  
27 was reduced to give participants more time to perform gestures.  
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- 34 (4) *Practice panels* were shown after consecutive poorly timed or executed  
35 movements. The practice panel offered a simplified game environment without  
36 obstacles wherein participants could practice the movement.  
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- 41 (5) *End-of-level* rewards: Trophies were rewarded at the end of each level in  
42 accordance with the number of dodge and style points achieved. One trophy  
43 indicated a lower level of mastery while three trophies was associated with the  
44 highest level of mastery. Additional rewards such as unlocking characters and  
45 leader board standings could also be reviewed as end-of-level KR biofeedback.  
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53 Sample play with the game adapted with biofeedback can be seen [ link removed for  
54 blinding].  
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## ***Phase 2: In-home evaluation***

Usability and impact of the biofeedback were evaluated in a 4-week home-based intervention. Inclusion criteria were: persons 8-18 years old with CP, MACS I-III, ability to co-operate, understand, and follow simple instructions, and, typical or corrected to typical vision and hearing. Exclusion criteria were: history of unmanaged epilepsy that may be triggered by video game play, having received a botulinum toxin treatment within 3 months or constraint-based movement therapy within 6 months of the study enrolment, visual, cognitive or auditory disability that would interfere with gameplay. The protocol was approved by the [names removed for blinding] Research Ethics Boards. Caregivers and participants gave written informed consent or assent as appropriate.

Each participant took home a laptop with the game software and a Myo Armband to play for four weeks. Before playing alone, the researcher gave one or two training sessions to ensure participants could operate the system and understood the objectives and controls of the game. Participants created a self-defined practice schedule with the assistance of their caregiver and an occupational therapist (the suggested goal was 3-5 times per week, 30 minutes per day) (Golomb et al., 2009). At home, participants selected which level to play, but more difficult levels were unlocked only after finishing easier ones. Once per week, the researcher visited the participants to evaluate their motivation, adherence, collect system logs, and to record subjective biofeedback-related observations.

## ***Outcome Measures***

The system automatically logged biofeedback usage data (e.g. dodge points, style points, practice panels presented) and physiological data (i.e. EMG, arm kinematics) for

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3 post-hoc analysis. At the end of the four-week trial, participants completed a semi-  
4 structured interview and a custom game-feedback questionnaire with the researcher.  
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7 These were used to understand how the added biofeedback impacted the participants'  
8 experience with the game. The questionnaire was based on validated questionnaires for  
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10 measuring usability (System Usability Scale (SUS) (Brooke, 1996) and enjoyment  
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12 (Flow Short (Engeser & Csikszentmihalyi, 2012)) and questions developed during a  
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14 previous study of interactive computer play games for young people with CP  
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16 (Hernández, Khan, Fay, Roy, & Biddiss, 2018). Examples of open questions used to  
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18 facilitate conversations during the semi-structured interview include: 'How did the  
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20 score change how you played the game?' and 'What helped to make the game easier to  
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22 play?' (Appendix A).  
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### 30 **Data Analysis**

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32 To resolve the Phase 1 research question: '*how user-centred biofeedback can be*  
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34 *integrated into an existing commercial video game to promote motor learning?*' an  
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36 audit trail was generated that integrated participant feedback, researcher observations,  
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38 and clinician input. This audit trail was reviewed, and a list of design specifications was  
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40 tabulated to guide the integration of biofeedback into video games for motor therapy.  
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44 To evaluate the Phase 2 research question: *is the biofeedback implementation (i)*  
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46 *efficient, (ii) effective, and (iii) engaging from the perspective of its users for promoting*  
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48 *quality movement during a therapy game focused on hand gestures?*, the following  
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50 variables were analysed:  
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- 54 (1) *Efficiency*: The system was considered efficient if participants reduced the use of  
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56 compensatory arm movements immediately after a speed-change biofeedback  
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58 event. The difference in resultant angular velocity variability of the forearm  
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3 between the five seconds before and five seconds after the speed-change  
4 biofeedback event was calculated. We refer to this variable as the “*change in*  
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9 *arm movement.*”

- 10 (2) *Effectiveness*: The system was considered effective if task performance  
11 improved over time. Three indicators of task performance are the “*dodge point*  
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32 *rate*” (dodge points accumulated per minute of play, linked to correct timing of a  
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60 gesture) and “*style point rate*” (style points accumulated per minute of play,  
linked to co-contraction quality). The number of “*practice panels shown per*  
*minute*” was calculated as an indicator of the need for biofeedback. Note:  
practice panels are presented when consecutive poorly timed or executed  
movements are performed. As such, indicators of improved performance are:  
*increasing* dodge point rate, *increasing* style point rate, and *decreasing* number  
of practice panels shown per minute.
- (3) *Engagement*: The system was considered engaging if participants chose to  
review the KR biofeedback provided at the end of each level reporting on their  
success in the game (e.g., the trophies awarded). This variable, ‘*review choice*’  
is the proportion of opportunities participants took to see end-of-level KR  
biofeedback.

To evaluate the *efficiency* of the biofeedback for promoting higher quality  
movement, the *change in arm movement* before and after a speed-change biofeedback  
event was compared using a dependent-samples t-test with alpha risk set to 0.05 (Chu et  
al., 2009; Müller & Sternad, 2009). *Engagement* is described as the percentage of  
instances participants chose to review end-of-level feedback. *Effectiveness* is described  
as the practical changes in performance (dodge points, style points, practice panels) in  
playing a typical 2-minute level at the beginning and end of the intervention. To

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3 understand how the *efficiency*, *effectiveness*, and *engagement* with the biofeedback  
4 system changed over time, a generalized linear mixed-effect model (GLMM) was  
5 constructed for each of the above-described variables. The model takes into  
6 consideration variations between participants and the game levels. Specifically, all  
7 models included *practice time* (cumulative minutes spent playing the game) as a fixed  
8 effect, a random intercept for *participants* and a random *participant\*game level*  
9 interaction effect since individuals self-selected which levels to play. Adjusted odds  
10 ratios (aOR), for binomial responses, and coefficients per unit increase from the mean  
11 observed value and their 95% confidence intervals (CIs) were calculated for each  
12 covariate. Alpha risk set to 0.05 was considered significant (see Supplementary Material  
13 A for full GLMM model specifications) (Casals, Girabent-Farrés, & Carrasco, 2014).  
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28 Lastly, post-intervention gameplay questionnaire data were used to further  
29 assess the impact that added biofeedback had on the game experience and usability. The  
30 5-point Likert scale data from the questionnaire were reported via descriptive statistics  
31 (median, inter-quartile range (IQR)). Demographic characteristics and volume of  
32 practice are described first for each phase to provide context.  
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## 41 **Results**

### 42 ***Phase 1: Design approach***

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45 Participatory design partners were nine young people with CP, 9-23 years old. Four  
46 were at MACS level II and five at level I. There were three female and six males.  
47  
48 Participants engaged in gameplay for 30±11 minutes of a typical 60-minute session.  
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50 Three participants completed three sessions, two participated in two sessions and four  
51 did one session. Feedback collected during these design sessions was compiled and  
52 changes in five key areas were identified: game flow/objectives, feedback elements,  
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3 adaptive difficulty settings, aesthetic considerations and technical issues were identified.

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5 Table 1 below details the changes made based on participant comments.

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10 **Table 1.** Design changes to integrate biofeedback into a commercial game (Dashy  
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12 Square)

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18 ***Phase 2: In-home evaluation***

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21 Nineteen participants played the biofeedback-enhanced therapy game at home for four  
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23 weeks. There were ten females and nine males, 8-17 years old ( $11.7 \pm 2.5$  years). Seven  
24  
25 participants were considered MACS level II and 12 were at level I. Seven had mixed  
26  
27 tone, one had mild dystonia and 11 had spastic hemiplegia. During the four-week  
28  
29 intervention, participants played an average of  $17 \pm 9$  minutes/day,  $4 \pm 1$  days/week. Total  
30  
31 practice time ranged from 37-333 minutes across the 19 participants. Participants  
32  
33 averaged  $2815 \pm 2202$  repetitions over the course of the intervention.

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37 *Efficiency.* All participants adapted their movements immediately after  
38  
39 biofeedback as evident in Figure 1. On average, participants reduced *arm movement* by  
40  
41  $10.2 \pm 4.0\%$  in response to biofeedback ( $t_{18} = 7.68$ ,  $p < 0.001$ , 95% CI = -11.9 - -8.5%).  
42  
43 Participants continued to respond to the speed-change biofeedback across the  
44  
45 intervention as practice time was not a significant predictor in the model ( $p = 0.330$ , 95%  
46  
47 CI -0.738 – 0.246). A participant\*level interaction random effect was not observed and  
48  
49 was therefore removed from the model ( $\Delta AIC$  (akaike information criterion) = 0.809,  
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51  $p = 0.275$ , see Supplementary Material A).

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58 **Figure 1.** Participant specific box plots of task performance response to feedback

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3 *Effectiveness.* After accounting for participant and game level variance in the  
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5 GLMM, practice time was associated with: i. scoring points faster ( $p < 0.001$ , 95% CI  
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7 0.963 - 1.093, increase in *dodge point rate* per 60-minutes practice), ii. doing gestures  
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9 with higher quality co-contraction ( $p < 0.001$ , 95% CI 22.555 - 30.042, increase in *style*  
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11 *point rate* per 60-minutes practice), and iii. seeing fewer *practice panels* ( $p < 0.001$ , 95%  
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13 CI -0.047 - -0.025, fewer practice panels shown per minute of play for every 60-minutes  
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15 of practice). See Supplementary Material A for full model output including random  
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17 effects of participant and participant\*level interactions.  
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21 Practically this means that the average participant playing a 2-minute level for  
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23 the first time could expect 23 dodge points, 1598 style points and 5 practice panels. At  
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25 the end of the 4-week intervention, on a similar level, the same participant could expect  
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27 32 dodge points, 1729 style points and 4 practice panels.  
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30 *Engagement.* Participants chose to view their end-of-level KR biofeedback  
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32 65.4±22.4% of the time. Based on results of the GLMM, the *choice to view* end-of-level  
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34 KR biofeedback was not dependent on practice time ( $p = 0.557$ , aOR = -0.061, 95% CI -  
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36 0.265 – 0.261). This suggests that participants continued to engage with the end-of-level  
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38 KR biofeedback throughout the 4-week intervention. There was a small variance across  
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40 participants (random intercept aOR standard deviation = 0.841, 95% CI 0.552 - 1.282),  
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42 but including this as a random intercept improved model performance ( $\Delta AIC = 778.03$ ,  
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44  $p < 0.005$ ) suggesting that engagement with end-of-level KR biofeedback was, to some  
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46 extent, person-dependent. To this point, 16/19 participants remarked that they decided  
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48 to review their achievements as they aimed to get all the rewards in each level.  
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53 Lastly, Figure 2 shows the frequency distribution from the usability and  
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55 enjoyment questionnaire completed after four weeks of play. Overall, participants found  
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57 the game highly usable (Median=5, IQR=3-5) and partially-to-highly enjoyable  
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3 (Median=4, IQR=3-5). Semi-structured interviews with participants and caregivers  
4 revealed participants used different personal success indicators. For instance, one  
5 participant, Dylan (*pseudonym*) noted that he “[didn’t] care about trophies, [and it was]  
6 more about points”. While Tina “first tried to get three trophies, to get all characters,  
7 then tried to beat top scores”. Of the 19 participants, nine were motivated primarily by  
8 long term rewards (e.g. collecting trophies), seven focused on the immediate score, and  
9 three on their game rank relative to others. Participants and caregivers also remarked on  
10 the technical performance of the system and its impact on engagement. “When the  
11 system crashed, it made her frustrated and not want to play” – Anna’s mom. Conversely  
12 when the system worked well, it provided an immersive experience: “it felt like my  
13 hand was actually speaking to the computer” – Geoffrey.  
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30 **Figure 2.** Usability and enjoyment questionnaire responses.  
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## 33 34 35 36 **Discussion**

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38 Biofeedback interventions for people with CP historically have not implemented  
39 biofeedback in line with motor learning theory (MacIntosh et al., 2018). They generally  
40 provide information too frequently and offer the person little choice. This study aimed  
41 to integrate evidence-based and co-created biofeedback strategies into a home-based  
42 therapy video game. Required changes for a commercial game were identified through a  
43 participatory design framework. In-home evaluation of the new technology showed that  
44 evidence-based biofeedback could be integrated to create a highly usable system (i.e.  
45 efficient, effective and engaging). Key findings suggest that the biofeedback  
46 implementation in the therapy game was:  
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3 (1) *efficient* – participants responded immediately to in-level KP biofeedback  
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5 isolating hand movements while practicing at home,  
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- 7  
8 (2) *effective* – participants used KP biofeedback to improve their movement timing,  
9  
10 quality and mastery of the game,  
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- 12  
13 (3) *engaging* – participants often chose to review their end-of-level KR biofeedback  
14  
15 (e.g. trophies awarded) demonstrating autonomy and active engagement with the  
16  
17 system.  
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19  
20 Qualitative reports supported the above conclusions. Overall, participants  
21  
22 perceived the game as usable and enjoyable after playing for one month.  
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### 25 26 ***Recommendations for the effective design of biofeedback in therapy gaming*** 27 28 ***technologies*** 29

30  
31 Learning from our co-design and evaluation process, we present the following key  
32  
33 recommendations to consider when delivering biofeedback in therapy games:  
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35

#### 36 37 *Link game rewards to movement goals* 38

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40 There can be multiple short-, mid-, and long-term rewards that provide KP and KR  
41  
42 biofeedback in video games. The value that a player places on these different rewards  
43  
44 can vary greatly and different people may be motivated by different aspects of the  
45  
46 game. To be effective, it is crucial that each game reward is directly impacted by and  
47  
48 linked to the targeted therapeutic aim. Involving the end-user in the development and  
49  
50 testing phase to ‘stress’ the system is a valuable approach to uncover ways that  
51  
52 individuals may achieve game rewards while circumventing the therapy goal. For  
53  
54 example, in this project, initial design sessions revealed that participants could achieve  
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56 game rewards by pronating and flexing instead of extending at the wrist. Working  
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58 through this led to changes in the controller, which helped ensure participants were  
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3 required to do the intended therapeutic movement to collect rewards and succeed in the  
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5 game. Linking game goals to movement goals ensures that biofeedback is in fact  
6  
7 accurate, informative, and reinforces practice of therapeutic movement strategies.  
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### 10 11 *Provide a safe space*

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14 Video games are immersive environments where it is easy to get carried away in the  
15  
16 excitement. In therapy games, this can lead to poor quality movement execution. In  
17  
18 design sessions, we found that increases in game difficulty could result in participants  
19  
20 trying a flurry of low-quality gestures, straying away from the therapeutic aim. In  
21  
22 response, we introduced a practice panel which was intended to be a safe space in the  
23  
24 game to practice the high-quality therapeutic movements that would help them succeed.  
25  
26 Stopping the game, minimizing sounds and graphics, and eliminating the potential for  
27  
28 any negative in-game consequences, gave participants the opportunity to focus on  
29  
30 movement quality and adjust to the increasing difficulty of the game. Tutorials are  
31  
32 ubiquitous in video games. They usually help people learn contextual controls when  
33  
34 starting games (e.g. *Press 'A' to jump over the wall*). A therapy game can leverage the  
35  
36 established logic of traditional game tutorials by incorporating prescriptive feedback  
37  
38 towards the therapy aim. Instead of presenting tutorials mainly in the beginning of a  
39  
40 new situation, presentation can be dictated by how 'well' (e.g. how frequently or how  
41  
42 accurately) participants do the therapeutic movement. Continued opportunities for  
43  
44 prescriptive feedback in a safe space, when it is needed, can enable participants to build  
45  
46 competency in the game and in the therapeutic movements. However, it is important to  
47  
48 ensure these practice elements do not detract from immersion and game flow. If they  
49  
50 occur too frequently or take too long to complete, it may indicate an inappropriate  
51  
52 challenge for the participant. During design sessions we modified the frequency and  
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54 timing of the practice panel to find a balance that was perceived to be optimal by our  
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3 users.

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7 *Minimize presence to maximize impact*

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10 In traditional biofeedback interventions, when information is constantly given, the  
11 person can develop a dependency (Taylor, Dodd, McBurney, Graham, & Kerr Graham,  
12 2004). Literature suggests that certain techniques can improve performance and  
13 retention, including: varying the modality (e.g. visual, audio), providing a ‘fading’  
14 biofeedback schedule as a person improves, and only offering biofeedback when  
15 players are in a ‘target zone’ (Muratori, Lamberg, Quinn, & Duff, 2013; Timmermans et  
16 al., 2009). These techniques were employed in this therapy game intervention.

17  
18  
19 Participants track their immediate score with a counter and a progress bar accompanied  
20 by audio cues with each successful movement. This feedback was supplemented with a  
21 ‘bonus’ score that appeared when players were in a ‘target zone’ (achieving high quality  
22 co-contraction for extended periods). Then, as the participant’s achieved mastery of the  
23 game, the progress bars were removed, the ‘bonus’ was shown less frequently, and  
24 participants were able to choose whether to review their scores and rewards at the end  
25 of a level or skip directly to the next level. This type of autonomy can build investment  
26 in an activity (Bingham & Calhoun, 2015).

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28  
29 We have further summarized our learnings in an infographic ([link removed for  
30 blinding], and in Supplementary Material B). This infographic may serve multi-  
31 disciplinary teams building technologies to help people practice motor activities. It may  
32 be particularly useful to support engagement with mainstream game developers.

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35 Researchers should consider adapting professional games, especially when artistic and  
36 developer resources are limited. In this project, the company we partnered with was  
37 small (2-5 members) which allowed greater flexibility to make changes in the game.

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40 While adapting an existing game with demonstrated popularity has many advantages

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3 with respect to the quality of gameplay achieved, considerable time was invested  
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5 educating and working with the company to appropriately integrate biofeedback  
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7 elements. It is our hope that the infographic will facilitate these collaborations and  
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9 accelerate development of higher quality biofeedback therapy games.  
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### 13 ***Limitations***

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16 This study does not discuss the transfer of experiences in-game to daily activities.  
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18 Rather, it reports the direct biofeedback implications observed when performing motor  
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20 activities to control a video game. The customized feedback questionnaire was not a  
21  
22 validated measure but merely addressed key domains of usability and enjoyment.  
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24 Further, participants used self-directed practice schedules to maximize ownership and  
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26 motivation at home. Certain participants played infrequently some weeks (e.g. due to  
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28 school assignments or competing interests). Finally, changes in biofeedback thresholds  
29  
30 and game difficulty were manually adjusted in some cases by the researcher based on  
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32 their evaluation of the participant's competency and motivation. Future work should  
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34 further standardize how feedback is modulated as player competency increases at home.  
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For Peer Review Only



**Appendix A.** Open questions used to facilitate conversations during the semi-structured interview after 4-week in-home evaluation

a. Usability

i. Ease of play

1. What helped to make the game easier to play?
2. What helped to make the game harder to play?
3. Did you feel like you were in control of the game?
4. Did anything hold you back from playing the way you wanted?

ii. Strategy

1. Was there anything that you used when playing the game to help you succeed?
2. How did the score change how you played the game?
3. Did the characters change how you played the game?
4. What was your strategy to avoid the obstacles?
5. Name the game you have played that is most similar to this game.

iii. Focus

1. What was the most important part of the game for you?
2. If you could change any aspect of the game or your experience, what would it be? Unlimited budget and time.

b. Fun

1. What parts of the game did you find most fun?
2. What was your favorite moment or interaction?
3. What was your least favorite moment or interaction?
4. Which game mode do you like the best? (Jump, Dash, Fly), Why?

**Table 1.** Design changes to integrate evidence-based biofeedback into a commercial game (Dashy Square)

<b>I. Game flow/ objectives</b>	
a. Added calibration game to get session baseline for movements and biofeedback b. Changed from pass/fail to score-based objectives c. Linked reward schedule (unlocking trophies and characters) to movement performance <ol style="list-style-type: none"> <li>i. Completing movement at correct time (dodging obstacles) and with high movement quality*</li> </ol>	
<b>II. Feedback Elements</b>	<b>Feedback modulation schedule<sup>†</sup></b>
<i>1. In-level</i>	
a. Visual and sound effects indicating successful movement <ol style="list-style-type: none"> <li>i. successful dodge</li> <li>ii. movement quality score achieved</li> </ol> b. Increment <ol style="list-style-type: none"> <li>i. Dodge score counter and progress bar</li> <li>ii. Movement quality score counter and progress bar</li> </ol> c. Visual effect on unsuccessful movement d. Reduce game speed on unsuccessful event with excess arm movement (poor hand movement isolation) e. Added movement-based animation cues to improve player timing	i. Movement quality score counter and progress bar are shown when performance status is 'great' ii. Dodge score progress bar is hidden after person develops competency
<i>2. Practice panel</i>	
a. Pause game and show practice environment <ol style="list-style-type: none"> <li>i. Remove excess animations/sound and simplify background</li> <li>ii. Show prescriptive animation and written cue of how to improve movement</li> </ol> b. Person completes two successful movements as practice	i. Appears when performance status is 'poor' at in-level checkpoint or at end of level ii. Appears when person reaches threshold number of consecutive unsuccessful movements (3-10)

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c. Bonus movement quality score awarded with visual and sound effect	
<b>3. End-level</b>	
<ul style="list-style-type: none"> <li>a. Show icon to view or skip end-level feedback</li> <li>b. Show dodge score counter and progress bar</li> <li>c. Show movement quality score counter and progress bar</li> <li>d. Run animations and sound effects for unlocked rewards (trophies and characters)</li> </ul>	<ul style="list-style-type: none"> <li>i. Person has option to view or skip feedback when performance status is 'good'</li> <li>ii. Movement quality score counter and progress bar are shown when performance status is 'great'</li> <li>iii. Person always views feedback after developing competency</li> </ul>
<b>†Modulating feedback according to performance and competency</b>	
<ul style="list-style-type: none"> <li>a. Performance thresholds <ul style="list-style-type: none"> <li>i. Determine when feedback elements are shown or hidden.</li> <li>ii. Based on percent of successful movements in-level.</li> <li>iii. Performance status: <ul style="list-style-type: none"> <li>1. <i>Poor</i> - &lt; 25% successful movements</li> <li>2. <i>Good</i> - 25% - 65% successful movements</li> <li>3. <i>Great</i> - &gt;65% successful movements</li> </ul> </li> </ul> </li> <li>b. Competency <ul style="list-style-type: none"> <li>i. After the person shows competency in the movement and game, certain feedback elements are hidden</li> <li>ii. Researcher determined competency at weekly evaluations</li> <li>iii. Usually after the person completes most levels on the easiest mode</li> </ul> </li> </ul>	
<b>III. Adaptive difficulty settings</b>	
<ul style="list-style-type: none"> <li>a. Added adjustable game speed</li> <li>b. Added adjustable performance status thresholds</li> <li>c. Added settings for binary switch or multiple gesture control</li> <li>d. Edited obstacles size and spacing to let players control with gestures</li> </ul>	

**IV. Aesthetics**

- a. Simplified backgrounds, options and level difficulty
- b. Fixed camera window orientation
- c. Reduced animation and sound after unsuccessful movements

**V. Technical**

- a. Changed tap controller input to Myo Armband
- b. Added functionality to
  - i. Accept binary inputs based on movement thresholds
  - ii. Accept multiple inputs based on gestures
  - iii. Accept movement quality scores
  - iv. Store and synchronize game scores and rewards with movement data

Requirements were identified during participatory design sessions by young people with CP, occupational therapists, and researchers. These changes aimed to improve biofeedback comprehension and link biofeedback to game goals.

\*Movement quality is based on physiological factors: forearm extensor/flexor co-contraction, resultant forearm angular velocity variability and predicted gesture

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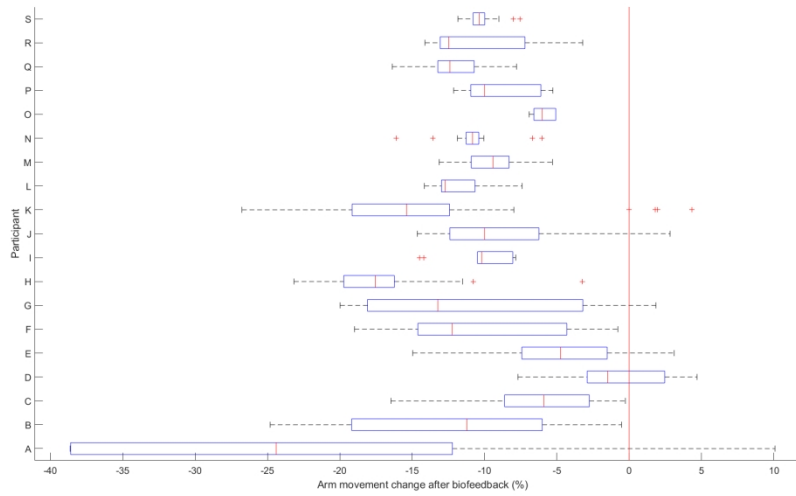


Figure 1. Participant specific box plots of change in task performance in response to biofeedback. Data left of the red vertical line indicates decreased arm movement (variance in resultant angular velocity) immediately after being given biofeedback. Left axis = participant ID. Bottom axis = percentage change in arm movement.

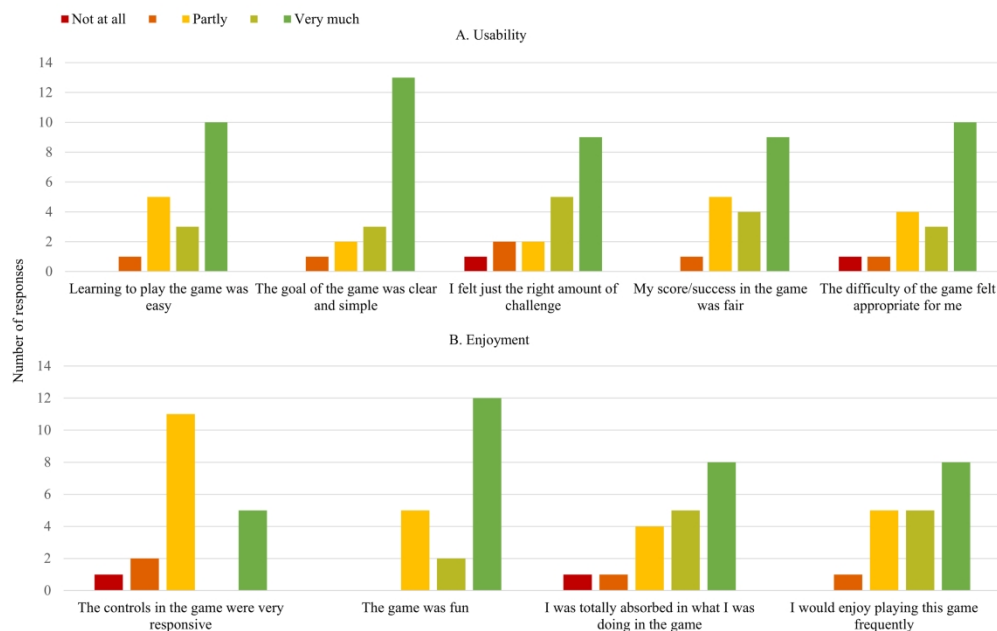


Figure 2. Usability and enjoyment questionnaire responses. Number of responses shown for each level of the 5-point Likert scale on all nine questions (N=19).

290x190mm (300 x 300 DPI)

## Supplemental A: Generalized Linear Mixed-Effects Models Details

Analyses were performed with MATLAB 2017b, Fit generalized linear mixed-effects model package (fitglm).

- Tables 1 and 2 below show model estimates and fit with model properties detailed below.
- Fixed effects: minutes of practice (exp),
- Random effects: participant (id), game level (level).
- Response variables:
  - o Measure 1: choice - The proportion of opportunities participants took to view their achievements.
  - o Measure 2: ChgArmMvmt – The percent change in arm movement before and after showing biofeedback
  - o Measure 3:
    - i. scrDodge – number of dodge points accumulated / minute of play
    - ii. scrStyle - number of style points accumulated / minute of play
    - iii. panelsperminute - number of practice panels shown / minute of play

**Table 1: Model Estimates**

		Estimate (95%CI)	SE	t	p-value
<b>†1 Measure 1: The proportion of opportunities participants took to view their achievements.</b>					
<i>Model 1- response variable: choice (683 observations)</i>					
Fixed (2)	Intercept	0.83 (0.36-1.31)	0.242	3.447	0.001
	practice time (60 min)	-0.06 (-0.26-0.14)	0.102	-0.588	0.557
Random covariance (std, 19)	Id	0.84 (0.55-1.28)			
<b>†1 Measure 2: The change in arm movement before and after showing biofeedback</b>					
<i>Model 2- response variable: ChgArmMvmt (515 observations)</i>					
Fixed (2)	Intercept	-10.18 (-12.32--8.05)	1.086	-9.378	<0.001
	practice time (60 min)	-0.25 (-0.74-0.25)	0.251	-0.976	0.33
Random covariance (std, 153)	id	4.42 (3.09-6.31)			
	level*id	1.13 (0.41-3.11)			

## \*1 Measure 3: Game performance

*Model 3a - response variable: scrDodge (1959 observations)*

Fixed (2)	intercept	13.03 (11.9-14.17)	0.579	22.493	<0.001
	practice time (60 min)	1.03 (0.96-1.09)	0.033	31.119	<0.001
Random covariance (std, 197)	Id	2.51 (1.8-3.49)			
	level*id	0.6 (0.51-0.71)			

*Model 3b - response variable: scrStyle (1959 observations)*

Fixed (2)	intercept	783.82 (724.5-843.14)	30.245	25.916	<0.001
	practice time (60 min)	26.3 (22.56-30.04)	1.909	13.777	<0.001
Random covariance (std, 197)	Id	130.36 (93.56-181.65)			
	level*id	39.39 (33.57-46.22)			

*Model 3c - response variable: panelsperminute (1959 observations)*

Fixed (2)	intercept	2.28 (2.12-2.43)	0.079	28.804	<0.001
	practice time (60 min)	-0.04 (-0.05--0.02)	0.006	-6.271	<0.001
Random covariance (std, 197)	id	0.34 (0.24-0.47)			
	level*id	0.11 (0.09-0.13)			

**Table 2: Final model fit characteristics**

	AIC	BIC	LogLikelihood	Deviance
Model 1	778.03 †2	791.61	-386.01	772.03
Model 2	3276.8 †2	3298	-1633.4	3266.8
Model 3a	6895.1 *2	6923	-3442.5	6885.1
Model 3b	22780 *2	22807	-11385	22770
Model 3c	21.54 *2	49.436	-5.77	11.54

AIC = Akaike Information Criterion, BIC = Bayesian Information Criterion



1  
2  
3 †1 Model 1 properties: Binomial distribution, logit link function and Laplace fit method. Model formula: choice ~ 1 + exp + (1 | id).  
4 Model dispersion = 1.

5 †2 Theoretical Likelihood Ratio Test showed non-significant addition of random id\*level interaction effect (df = 4,  $\Delta$ AIC =1.31,  
6 p=0.406).  
7  
8

9 †1 Model 2 properties: Normal distribution, identity link function and REMPL fit method. Model formula: ChgArmMvmt ~ 1 + exp +  
10 (1 | id) + (1 | level:id). Model dispersion = 5.36, 95% CI=5.00-5.74.

11 †2 Theoretical Likelihood Ratio Test showed significant addition of random id\*level interaction effect (df = 5,  $\Delta$ AIC =0.809, p=0.275).  
12  
13

14 †1 Model 3a-c properties: Normal distribution, identity link function and REMPL fit method. Model formula: [scrDodge or  
15 stylerDodge or panelsperminute] ~ 1 + exp + (1 | id) + (1 | level:id). Model dispersion = a) 1.309, 95% CI=1.267-1.352, b) 75.354,  
16 95% CI=72.941-77.847, c) 0.226, 95% CI=0.219-0.234.

17 †2 Theoretical Likelihood Ratio Test showed significant addition of random id\*level interaction effect for models 3a-3c (3a. df = 5,  
18  $\Delta$ AIC =-269.7, p=<0.001, 3b. df = 5,  $\Delta$ AIC =-309.5, p=<0.001, 3c. df = 5,  $\Delta$ AIC =-200.3, p=<0.001).  
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# Adding biofeedback to video games

Making a rehab video game takes input from clinicians, developers and players. Here are helpful tips for teams looking to add biofeedback into their video games

## Overview

## Tutorial

## Tips

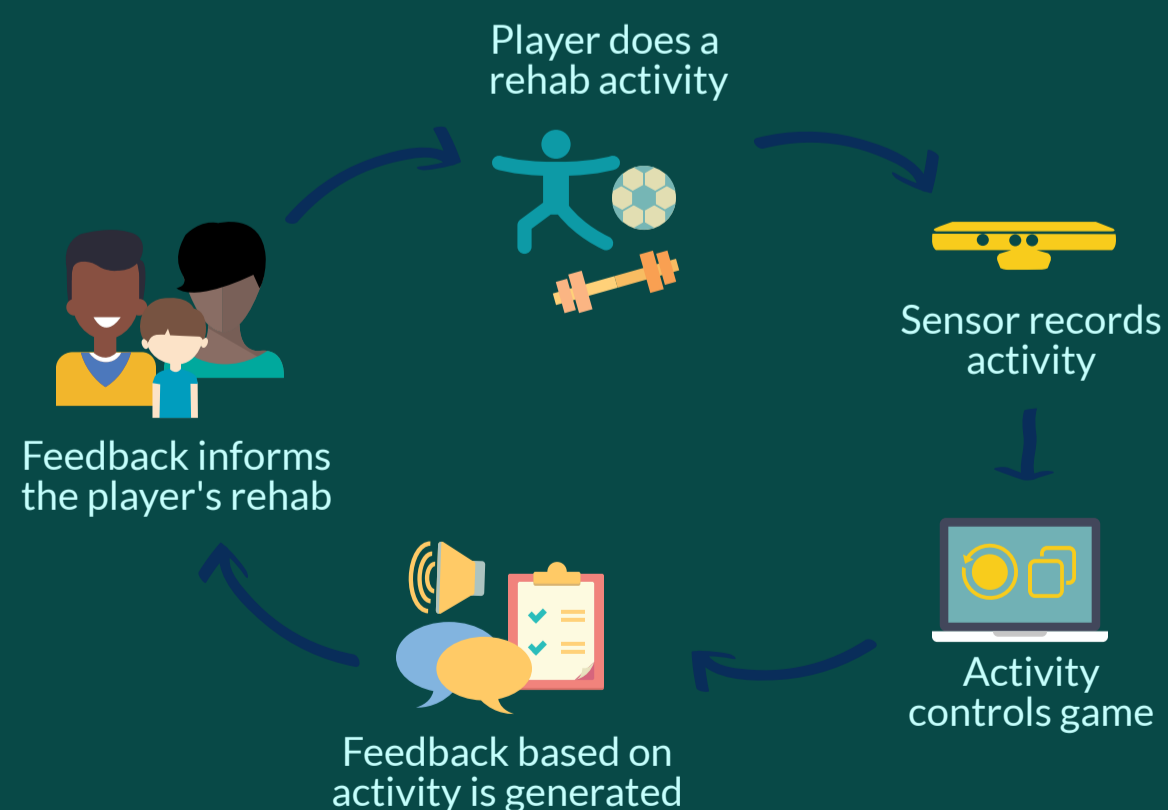


### What is biofeedback?

Biofeedback gives people information about their body. People use biofeedback to learn how to control their body better. Biofeedback can help in learning new skills.

### Biofeedback in games

Games can deliver biofeedback to promote learning:



Well integrated biofeedback closely links game feedback with the rehab activity.

### Biofeedback design characteristics



#### Feedback can be about:

- movement (speed, accuracy, distance)
- performance (good or poor)
- health data (heart rate, muscle activity)



#### Feedback can be delivered in different ways:

- audio
- visual
- tactile



#### Feedback can be given at different times:

- during or after a game
- when the player performs well or poorly
- with decreasing frequency as the player improves

Overview

Tutorial

Tips

Feedback should match the player's needs:


**Player goal**





<p><b>Practice</b></p> <p>Goal: increase repetitions</p> <p>↓ feedback</p> <p>↑ error tolerance</p>	<p><b>Mastery</b></p> <p>Goal: improve technique</p> <p>↑ feedback</p> <p>↓ error tolerance</p>
---	---

**i** Player needs can be determined by a clinician, themselves or a computer

**Skill difficulty**




<p><b>Simple skills</b></p> <p> Give instructional feedback</p>	<p><b>Complex skills</b></p> <p> Give success/failure feedback</p>
--	--

**i** Simple skills are usually a single step  
**Example:** wave hand up

Complex skills are usually many steps  
**Example:** shooting a basketball

**Player skill level**



<p><b>Novice</b></p> <p>↑ detail in feedback</p> <p>↑ instructions</p>	<p><b>Expert</b></p> <p>↓ detail in feedback</p> <p>↓ instructions</p>
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**i** Novices benefit from being shown how to do a movement  
**Example:** instructions

Experts should explore and find what works best for them  
**Example:** thumbs up

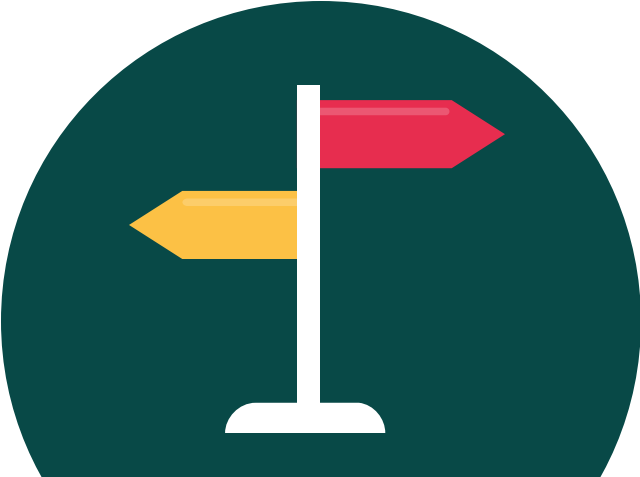
Overview

Tutorial

Tips

Here are 3 approaches to feedback that are hardly used even though they can be effective.

**Build in choice**



Giving players choice can help motivate them to learn new skills. They might choose to:

- get feedback
- ignore feedback
- customize feedback


**Less is more**



As players get more skilled, they should rely on themselves more than on the feedback. Only give feedback when they need it:

- once a skill is learned, no longer provide instructions
- only provide feedback when the player succeeds/fails

**Mix it up**



Changing how feedback looks helps the player become more independent. Variations can be:

- giving feedback at the end of the level instead of during the level
- going from more detailed feedback (e.g. instruction) to less detailed (e.g. a sound)

