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This thesis set out to address the effects of augmented visual feedback (VF) on postural control. The aim was twofold. First, to investigate the direct effects of VF on postural control; and second, to investigate the effects and potential benefits of providing PD patients with VF during balance tasks and after training, respectively. In this chapter, I will concisely summarize the findings collected along the way and discuss these against the background of the conceptual and methodological framework outlined in the General introduction (Chapter 1).

A brief summary of results

In the first chapters of this thesis, I presented experiments related to the direct effects of VF on postural control. In particular, I compared congruent VF with no or incongruent VF. VF was operationalized as a visual representation of the location of the center-of-pressure, displayed on a monitor mounted in front of a subject. The effects on postural control were quantified as changes in various statistics of the COP time series recorded during either quiet stance or rhythmic swaying. In Chapter 2, I used a static balance task with a fixed target to assess postural control during congruent and incongruent VF. While congruent VF was fed back directly to the subject, incongruent VF was produced by artificially delaying the visual feedback. The delay allowed for controlling the ‘degree of congruency’. Quality of performance was quantified by the standard deviation of the COP time series. As expected, performance improved during real-time VF as compared to when feedback was absent. For conditions with incongruent VF the quality of balance performance decreased. Interestingly, spectral analysis of the COP time series revealed that low frequency components, i.e. slow components of postural sway, displayed a monotonic increase in sway amplitude with increasing delay. In contrast, high frequency components, i.e. fast components of postural sway, showed significantly reduced sway amplitude for delays of 500-750 ms. Low- and high-frequency components of postural sway were thus influenced differentially by incongruent feedback suggesting that they reflect distinct components of postural control.

In Chapter 3, I used the same delayed-VF paradigm to make a direct comparison between patients with PD and healthy, age-matched controls. The question there was whether subjects with PD would be affected more by incongruent VF than healthy controls in a dynamic balance task. Subjects were asked to follow a moving target, which required shifting their weight within the limits of their base of support.
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For conditions without feedback and with real-time, congruent VF, subjects with PD performed lateral swaying motions with greater error and with more variable movement patterns than healthy controls. Error change scores revealed that patients with PD were nevertheless able to use VF to improve tracking performance. However, while controls were able to adapt to a certain amount of visual incongruity, patients with PD were not. These findings support reports that suggest an increased reliance on visual feedback in PD.

Chapter 4 reports measures of oscillatory neural activity derived from EEG recordings during the weight-shifting task used in Chapter 3. Movement-related activity was dominant in the alpha and beta bands (8-14 Hz and 15-30 Hz, respectively). The two groups did not display any differences under congruent VF. Yet, under incongruent VF the movement-related alpha and beta modulation discriminated between groups, at least in those regions that are thought to serve visual perception and motor activity, respectively. That is, the PD group showed more pronounced modulation than healthy controls in beta activity in M1, and in alpha activity in V1. Beta modulation in M1 is commonly considered to mimic cortical control of (rhythmic) motor performance while alpha modulation in V1 is believed to reflect (low-level) visual processing. Important here is that the results regarding cortical processing are in agreement with the behavioral data from Chapter 3 and support the idea that patients may rely more on congruent VF.

The subsequent chapters of the thesis concerned the clinical utility of using VF in a therapeutic setting. As mentioned above, patients with PD often suffer from reduced mobility due to impaired postural control. Although balance exercises form an integral part of conventional rehabilitative therapy, the effectiveness of existing interventions is limited. In Chapter 5, I presented the rationale for developing a VF-based balance training (VFT) program for use in this patient group, as well as a research design in order to investigate the feasibility and efficacy of such a program. The motivation for developing this specific training program was twofold: first, providing enhanced VF in the context of computer games can provide an attractive alternative to conventional therapy. Moreover, externally guided movements, rather than internally generated ones, may have a particularly high potential to help improve motor function in patients with PD. The objective of the corresponding pilot RCT was to determine whether a training program capitalizing on virtual-reality-based VF would be more effective than conventional training in improving standing balance performance in PD. Patients participated in a five-week balance-training
program. They were randomly allocated to an experimental group that received balance training using augmented VF or a control group that received conventional balance training. I hypothesized that balance training based on VF would show greater improvements on standing balance performance than conventional balance training.

The results of this pilot RCT are reported in Chapter 6. First and foremost, VFT was feasible to implement in a therapeutic setting and took place without adverse events. As for the effectiveness, change scores for all balance measures favored VFT, but the change in neither the primary outcome measure nor in any other outcome differed significantly between groups. Put differently, VFT could not be established to be superior over conventional balance training.

Further investigations

The studies in Chapters 2 and 3 did not only reveal that VF can improve performance but also that incongruent (delayed) VF impairs balance performance. Patients with PD performed generally worse than healthy controls and appeared more susceptible to incongruent VF. Chapter 4 addressed cortical activation during a postural task, and provided evidence that incongruent VF apparently involves more cortical resources in PD. Trying to modify this via VF-based training, however, failed, or rather VF-based training did not outperform traditional balance therapy in that regard (Chapter 5 and, in particular, Chapter 6). This raises several questions:

(a) Did the group that trained with VF show greater improvements in posturographic assessments than controls, when using congruent (i.e. real-time) VF?

The longitudinal analysis of the effect of the intervention in Chapter 6 considered only functional improvements. Unfortunately, assessments of functional balance capacity suffer from ceiling effects that limit the capacity to measure improvement as performance approaches the maximum. This may explain the lack of a training effect in this study, at least in part. Posturographic analyses can provide useful supplementary information about (changes in) postural control. One may expect that the group that trained with VF score better on posturographic assessments that make use of VF. In particular, it can be hypothesized that the VF-group is, upon completion of the training program, better able to use congruent VF. As was proposed in Chapter 5, posturographic and EEG data were also collected upon
completion of the training program, as well as at the follow-up assessment. Since a formal analysis of these data is not part of this thesis, I will use this space here to discuss these results at a qualitative level.

Fig. 7.1 summarizes adaptation scores over the period of the study for subjects (compare also Figs. 3.5-7 in Chapter 3). The second column demonstrates the results for $\text{VF}_r$, that are of particular interest for answering the present question. The data for the pre-training assessment should be very similar for both groups, as at that point no intervention had yet taken place. However, this appears not to be the case, as the group that received regular balance training shows greater reductions in $\Delta \text{Error}$ and $\Delta \text{Var}$ already during the pre-assessment session, as well as a greater increase in $\Delta A_{\text{norm}}$. Although these differences may not be statistically significant, it is more than a little unsatisfying that these belong to the most prominent changes.

Furthermore, no clear patterns emerge from these data, and the most striking characteristic perhaps seems to be the large variability within the groups. Coming back to the question, it seems that VF-based training did not help the subjects in this group to better coordinate their movements with the VF, as the VF group does not appear to decrease $\text{Error}$ or $\text{Var}$ over time, nor increase movement amplitude $A_{\text{norm}}$.

(b) Did the group that trained with VF experience greater negative effects of incongruent VF than the control group?

Patients with PD seem to depend on visual information more than healthy controls. It is hence not inconceivable that a training program that explicitly focuses on using VF will strengthen this dependency. The collected data allow for a qualitative assessment of this question: if this were true, the incongruent VF would have led to greater negative effects in the group that trained with VF than the group that received conventional balance training.

The two rightmost columns of Fig. 7.1 show the results for incongruent VF. The change scores for $\Delta \text{Error}$ for $\text{VF}_{250}$ and $\text{VF}_{500}$ do show a tendency to become progressively more negative for the VF-group, but again, these differences are likely not statistically significant. In other words, the present results do not suggest in any way that subjects were made more dependent on VF following VF-based intervention.

(c) Do measures of cortical activation change over the course of the intervention?

According to the results of Chapter 4, there were no significant differences in cortical activity between the patients with PD and healthy controls when congruent VF was
provided. Under incongruent VF, however, the PD group displayed higher normalized beta modulation in M1, and higher normalized alpha modulation in V1 than healthy controls.

Beta power modulation might reflect the relative usability of the VF: if there is high uncertainty in feedforward estimations from the internal model (as in the case of incongruent VF), post-movement beta power synchronization will be low. If, on the other hand, feedforward estimations were reliable (as in the case of congruent

![Graph](image)

**Fig. 7.1** Effects of VF-based balance training on posturographic outcome measures for the VF-group and the control group that received regular balance training. Shown are adaptation scores for the outcomes $\text{Error}$ (top panel), $\text{Var}$ (middle panel), and $\text{A}_{\text{norm}}$ (lower panel), for either of the four feedback conditions, at the three time points pre-training (black), post-training (grey), and at follow-up (white). Note that the adaptation scores reflect the change in performance relative to the performance at the beginning of the first trial at the pre-training assessment; for instance, $\Delta \text{Error}$ at post-training is computed by taking the difference between $\text{Error}$ at the end of the last trial of the second assessment session (post-training) and $\text{Error}$ at the beginning of the first trial of the first session. Hence, the outcome for pre-training reflects changes in performance that came about during the first assessment, whereas the outcome for post-training reflects changes in performance that came about during the entire period encompassing the first assessment, the 5-week training program, and the second assessment session.
VF), beta power synchronization should be high. In the process of motor adaptation, the mismatch between predicted sensory outcome and actual sensory outcome is used to update the internal model. One may thus assume that with motor training updates of the internal model are issued. As such, the beta power modulation should decrease over time – even in the absence of changes in posturographic measures.

Fig. 7.2 and Fig. 7.3 show the longitudinal data for those effects that were found to show significant differences between groups in Chapter 4. Fig. 7.2 shows the beta power modulation in M1 for the three sessions (cf. Fig. 4.3 in Chapter 4). As expected, beta modulation in the motor cortex was relatively low for VF\textsubscript{no} and did not change much over time (although a decreasing trend is visible). For VF\textsubscript{rt} and VF\textsubscript{250} beta modulation appeared to decrease between the first and second assessment, and then again increased for the third assessment. These results are likely not statistically significant however. Fig 7.3 shows the alpha modulation in V1 over time. Note that in Chapter 4, alpha modulation in V1 was found to differ between healthy subjects
and patients with PD during incongruent VF. Here alpha modulation appears to increase with incongruent VF as compared to no or real-time VF.

General discussion

In this thesis, I highlighted several effects of VF on postural control from different perspectives. Here I will revisit a number of issues presented in the General Introduction.

Postural control is a complex process. It preserves or changes postures by restricting or allowing body segments to move relative to one another (Horak, 2006; Massion, 1994; Peterka, 2002). Besides regulating the postural tone to control body alignment, it also functions to maintain a state of balance, that is, resist perturbations. Vision plays a major role in the control of posture. This powerful pathway was utilized to deliver a supplementary form of feedback about movement performance (biofeedback), either to help enhance motor performance, or to help create situations of conflicting feedback.

Utility of VF in balance training in PD

Disease management for patients with PD has long aimed to reduce disease symptoms. Physical training and exercise is a fundamental and indispensable component of treatment (Goodwin et al., 2008; Morris, 2000). It can induce improvements beyond those of pharmacological or surgical intervention. However, training interventions with respect to balance or postural control have yielded variable results (Allen et al., 2011; Tomlinson et al., 2013). Biofeedback offers a promising means to enhance motor learning in rehabilitation (Huang et al., 2006), for instance when delivering balance therapy (Lee, Thrasher, Fisher, & Layne, 2015; Nichols, 1997). Though biofeedback can be delivered through other modalities (e.g., haptic, auditory) or combinations of modalities, the effects have been most extensively studied for visual feedback (VF) (Sigrist, Rauter, Riener, & Wolf, 2013).

The pilot RCT presented in Chapters 5 and 6, was – to the best of my knowledge – the first RCT to investigate the feasibility and effectiveness of a balance training program based on augmented VF specifically designed for patients with PD. An important outcome was that VF training is feasible for individuals with PD, safe to use and considered suitable for use in a (group) setting where continuous one-on-one supervision is not required. The study did not support the hypothesis that VF-
based balance training is superior to conventional balance training in improving standing balance performance as measured by the primary outcome measure, functional reach. Most outcomes showed trends clearly favoring VFT. Was this pilot RCT powerful enough to detect statistically significant effects? A post-hoc power analysis revealed that sample size had indeed been a limitation of this proof-of-concept study, suggesting that the variability within the groups of patients was higher than expected. Furthermore, only for the outcome walking speed did the difference in change score approach the minimal detectable change. For all other outcomes, the magnitude of the improvements did not appear to be clinically relevant, regardless of the type of intervention. An ancillary analysis of within-group effects failed to show a significant treatment effect over time for either intervention. This does suggest that the training volume implemented in this pilot study was insufficient to elicit substantial training-related improvements. This may be addressed by increasing the number of sessions, by increasing the exercise intensity, or by adding booster sessions. After all, participants from both groups rated their level of exertion on average as ‘light’. And, patients worked in pairs at each workstation, which in the case of VFT meant a great reduction in time spent practicing. In future forms of VFT this may be resolved by the development of multiplayer games.

General principles of training and motor learning state that exercises are most effective when they are task-specific, progressively increase in intensity, and include considerable variation. This holds irrespective of whether the training occurs with or without VF. Postural control is ‘naturally’ task-specific, but it is in itself not a task. In rehabilitation, it is furthermore of great importance to train functional tasks; the question hence remains whether VF-based balance games are a valid instrument to train postural control. Sigrist and co-workers (2013) noted that in VF paradigms, the visualized task parameter often becomes part of the task as it constitutes the optimal source of feedback. That seems to be especially true for balance games, where the focus of attention is with the avatar. In the present configuration, the balance games provided concurrent (i.e. real-time) feedback. Whether concurrent feedback or terminal feedback (after the task is completed) is most effective depends on the complexity of the task (Sigrist et al., 2013), but whether this is the case for postural control is as of yet unclear.

In exercises that challenge postural control, the principle of progressive overload can be addressed primarily by changing task difficulty. In the case of the balance
games used in Chapter 6, this was realized mainly by varying task parameters like visual speed, number of virtual obstacles, and sensitivity of the hardware on a subject-to-subject basis. Though VR-based technologies do allow for the systematic and fine adjustment of parameters that influence task intensity, little is known about which of these task parameters are actually the most relevant. Finally, due to the experimental nature of the balance games, and the high costs associated with game development, variation of exercises was limited, at least compared to the potential for variation in the control intervention. In my opinion, for VF-based balance exercises to become effective tools in rehabilitation the greatest challenge remains to establish what constitutes valid, task-specific postural exercise.

Utility of VF to assess postural control

PD patients appear to rely more on visual guidance or feedback, in postural tasks (Azulay et al., 2002; Bronstein et al., 1990; Maurer et al., 2003; Vaugoyeau, Viel, Assaiante, Amblard, & Azulay, 2007) as well as in other tasks like reaching (Cooke, Brown, & Brooks, 1978; Majak, Kaminski, Gentile, & Flanagan, 1998). Keijsers et al. (2005) hypothesized that increased visual dependence in PD may serve as a compensatory mechanism for reduced proprioceptive feedback. Due to the partially redundant sources of kinesthetic information, this dependence might become apparent only in conditions with conflicting sensory information. An excellent way to create conditions of congruent and incongruent VF is by adding a time delay. Delayed VF will cause a mismatch between the expected sensory consequences of a given motor command and the actual sensory consequences as visualized by the VF (Shadmehr et al., 2010).

In the rhythmic swaying task for the cross-sectional comparison between patients with PD and healthy controls, incongruent feedback increased error scores (Chapter 3). Control subjects, however, managed to decrease their error over the course of the experiment, paired with improvements in movement variability and movement amplitude. This showed that – although challenging at first – these subjects were able to adapt to small delays. For patients with PD, improvements were not that substantial. Presumably, time-delayed VF was more difficult to suppress in patients with PD than in healthy age-matched controls and these results thus seem to be in line with previous findings (Azulay et al., 2002; Bronstein et al., 1990; Maurer et al., 2003; Vaugoyeau et al., 2007). Note that healthy older adults already appear to rely more on VF than younger individuals (Yeh et al., 2014).
Given the motor improvements associated with externally triggered movements, many studies have been undertaken to identify neural correlates of these improvements (see for instance, Cunnington, Iansek, Bradshaw, & Phillips, 1995; Debaere et al., 2003; Elsinger et al., 2006; Halsband et al., 1994; Jahanshahi et al., 1995; Oswal et al., 2012; Praamstra, Stegeman, Cools, & Horstink, 1998; te Woerd et al., 2015). VF may induce similar changes in neural activation as cueing, as they likely use similar underlying mechanisms. Tan, Wade, and Brown (2016) found that post-movement beta synchronization negatively correlates with the uncertainty in predictions made by an internal model. As cortical post-movement beta synchronization is reduced in patients with Parkinson’s disease (Pfurtscheller et al., 1998), this would indeed be in accordance with a greater reliance on sensory feedback (Tan et al., 2016). In conditions of unfamiliar or unreliable feedback, (pre-)existing motor programs become invalidated. Current sensory feedback needs to be integrated in order to update the internal model (Shadmehr et al., 2010). Beta power modulation might thus reflect the relative usability of the VF and/or drive motor adaptation. The results in Chapter 4 revealed significantly greater normalized beta modulation in the motor cortex of patients with PD. With incongruent VF, the PD group showed an increase in M1 beta activation whereas healthy controls showed a decrease in the level of M1 activation. Though these results are far from conclusive and warrant further study, it thus appears that in the presence of incongruent VF, the modulation of beta activity was suppressed in the healthy controls, but not in the patients with PD. These results might thus be interpreted as that the relative uncertainty in the feedforward estimations in healthy controls is higher in conditions with VF than without VF.

Concluding remarks

As it stands, the efficacy of VF-based training for patients with PD appears limited. Augmented visual feedback training did not provide additional benefits over conventional balance training. Certainly, technological developments are ongoing, creating possibilities to provide larger groups with even more customized training applications. Nevertheless, finding a solution to best address the large between-subject variability will remain challenging. As mentioned before, this variability may reflect the various (compensatory) strategies that patients use to integrate visual information in their motor behavior. Larger data sets may allow to disentangle these
factors by stratifying patient characteristics. Easier accessibility of the here-applied training manipulation will also provide possibilities to increase training intensity and volume. Crucial for determining the efficacy of any VF-based balance training is to collect high-quality evidence in the form of RCTs.

I furthermore conclude that congruent VF can help improve postural control. Adaptation to incongruent VF is, on average, different for patients with PD and healthy controls. Delayed VF as it was implemented here thus was a suitable method to study the dependence on VF. Furthermore, incongruent VF appears to be associated with differential neural activation in areas related to movement control and visual processing in patients with PD and healthy control. The role of beta activity as a neural controller of (rhythmic) movement that is now emerging from the literature appears to be a promising avenue for research in the coming years.