Standing Well

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Chapter 8

Summary and discussion

8.1. Summary

The aim of this thesis was to 'open the neural black box', i.e. the central nervous system (CNS), and examine its workings during a visual-vestibular conflict. To induce a visual-vestibular conflict I focussed on various manipulations of visual stimuli, whereas the vestibular cues were not manipulated; thus, while keeping the participants upright. In this thesis it is proposed that the CNS workings during a visual-vestibular conflict include an internal model of verticality, as is proposed by the motion sickness theory (MST). More specifically, a visual-vestibular conflict is thought to cause an internal mismatch between the actual body state, that is, postural orientation and sensory cues on the one hand, and its neural representations as provided by an internal model of verticality on the other. I assume these internal mismatches to affect specific motor and perceptual responses. In order to reveal the workings of the CNS during a visual-vestibular conflict, the patterns of these motor and perceptual responses were monitored. The studied motor and perceptual responses included postural sway, the subjective visual vertical (SVV), visually induced motion sickness (VIMS), and in one study also roll-vection.

In a first attempt to examine the conditions under which a visual-vestibular conflict can be induced, we focussed on one crucial aspect of visual stimuli: the presence or absence of visual motion. To date, nearly all studies on the influence of a visual-vestibular conflict tested only the effects of visual motion stimuli on motor and perceptual responses. However, the perhaps obvious contrast with static visual stimuli (with the same content) had never been tested. Thus, it was unclear whether motion is both a necessary and a sufficient condition to induce a visual-vestibular conflict. To that end, in **Chapter 2** we exposed participants to motion and still images, adapted from a popular first-person shooter game, in separate sessions. Before, during, and after exposure, participants rated their VIMS symptoms, and data on postural sway was obtained using a force platform. Postural sway was characterised by both global parameters and parameters related to the correlational structure of the centre of pressure time series. Results showed, in line with existing literature, that VIMS scores were significantly increased directly after exposure to the motion images, but not by the still-images. However, to our surprise, postural sway was significantly increased after exposure to both motion- and still images, which suggests that motor responses are (partly) dissociated from VIMS effects during a visual-vestibular conflict. Possibly, the equal increases in postural sway were caused by visual effects that were present in both still and motion images. Concluding, these results showed that VIMS symptoms and postural parameters are not similarly affected by viewing visual motion stimuli.

Next, in **Chapter 3** we investigated the influence of another visual manipulation on the visual-vestibular conflict: stereoscopic 3D.

With its increasing popularity, the public health concern that viewing 3D motion stimuli causes significant adverse effects is growing. Moreover, 3D is proposed to potentially cause more adverse effects compared to viewing 2D due to a more pronounced visual-vestibular conflict. To that end, in **Chapter 3** we first studied whether viewing a 3D motion stimulus caused an increase in VIMS and postural sway. Participants viewed a 3D documentary in a cinema, where we obtained data on VIMS and postural sway before and after the exposure. A significant increase in VIMS as well as in postural sway was observed after exposure as compared to before; which we ascribed to a visual-vestibular conflict that influenced both VIMS and postural orientation. However, in this experiment we were not able to include a condition in which participants viewed the same stimulus in 2D. The question whether viewing 3D motion stimuli would cause a larger visual-vestibular conflict, resulting in more VIMS and postural sway as compared to viewing 2D stimuli, was thus left open. No other study had yet addressed this question.

In order to fill this knowledge gap, in **Chapter 4** we used an experimental design including a 2D and a 3D condition in which participants watched the same motion stimulus as in **Chapter 3**. For practical reasons a commonly available 55 inch TV-screen was used to display the motion stimuli. We expected that 3D motion stimuli would cause a larger visual-vestibular conflict compared to 2D stimuli, because of their increased naturalness. Again, participants rated their VIMS symptoms, and we obtained data on global and structural parameters of postural sway. To our surprise, VIMS reports revealed that after both 2D and 3D exposure viewers only experienced mild oculomotor and disorienting symptoms, without substantial nausea, as was observed in the cinema (**Chapter 3**). Moreover, postural sway was significantly and equally increased after viewing both 2D and 3D stimuli. This seems to suggest that stereoscopic 3D stimuli do not necessarily cause a larger visual-vestibular conflict, as inferred from the VIMS results and postural parameters, compared to viewing 2D stimuli. The lack of difference can be explained by the fact that the 3D-effects in this documentary were optimized for viewing in a cinema (as in **Chapter 3**), whereas the projection on the TV-screen (as in **Chapter 4**) caused quarantining of the visual input; in other words, the visual input was set aside by the CNS.

As outlined in **Chapter 1**, especially visual cues that contain information about Earth-verticality, i.e. Earth-fixed cues, are proposed to suppress the influence of visual motion on a visual-vestibular conflict. Yet, no study had experimentally addressed the question how influential these visual Earth-fixed cues really are. In **Chapter 5** we therefore aimed to unravel the effect of an Earth-fixed visual manipulation, presented together with roll-motion around the line of sight, on a visual-vestibular conflict by measuring motor and perceptual responses. We exposed participants to visual roll-motion, with and without an Earth-fixed frame, while obtaining data on postural sway, the SVV and VIMS symptoms. Results showed that the presence of a visible Earth-fixed frame consistently decreased the effect of the visual roll-motion on postural sway, SVV deviations and VIMS symptoms. These findings thus showed that, as hypothesized, a visual Earth-fixed cue can significantly reduce a visual-vestibular conflict and the respective motor and perceptual effects caused by roll-motion. Moreover, the observation that all motor and perceptual responses were affected in a similar way by an Earth-fixed cue and roll-motion, are an indication for a CNS working mechanism that resembles characteristics of the MST, as I will elaborate on further below.

In **Chapter 6** we approached the internal mismatch from another direction by examining a poorly understood group of patients that regularly report aggravation of vestibular symptoms (such as postural unsteadiness and nausea) by visual stimuli, often without a clear neurological cause. Individuals with such symptoms are known as visual-vestibular mismatch (VVM) patients. We first aimed at getting a better insight into the underlying neural mechanism of VVM by examining the same motor and perceptual responses as studied in **Chapter 5**: postural sway, the SVV and VIMS. Second, we investigated whether motion around the line of sight is a necessary condition to aggravate their motor and perceptual symptoms, or whether a stationary visual stimulus would provoke equal increases in VVM symptoms. We exposed VVM patients and age-matched controls to a visual pattern that rotated around the line of sight in one session, and in another session to the same, but stationary, pattern. A first finding was that patients always swayed significantly more and reported more severe VIMS symptoms than the healthy controls, irrespective of the stimulus type they were exposed to. Secondly, VVM patients and controls both exhibited an increase in postural sway and VIMS after prolonged exposure to roll-motion, while the SVV was not affected. Only the VVM patients, however, reported significantly higher VIMS scores after exposure to roll-motion compared to scores after exposure to a stationary stimulus. Despite the large variability observed, and a rather inhomogeneous patient group, these findings showed that VVM patients do differ from healthy controls on motor and perceptual responses and that visual roll-motion is a crucial factor in aggravating VVM symptoms. A possible explanation for these findings is a persistent neural visual-vestibular integration deficit that leads to inaccurate neural representations, which are responsible for the observed VVM symptoms. Yet, further research should focus on unravelling the exact underlying neural mechanisms and deficits.

Finally, in **Chapter 7** we investigated the effect of another visual manipulation on the visual-vestibular conflict: the depth order, also called fore-background segregation. Intuitively, one would expect that visual factors related to this fore-background segregation, such as stimulus size and object density, are able to differentially influence the visual-vestibular conflict. More specifically, we assumed that if a visual factor belonging to the background is present in the background pattern, it would increase the visual-vestibular conflict; while it would suppress the visual-vestibular conflict when presented in the foreground. Based on the observation that the number of objects (density) under normal circumstances differs between the fore- and background, we asked whether varying the density would interact with the fore-background segregation in the modulation of the visual-vestibular conflict. To that end, we included postural sway and roll-vection as the motor and perceptual responses to be studied. Moreover, previous research has shown that these responses are affected in a similar way during exposure to visual motion, suggesting a common neural mechanism. We therefore measured postural sway and roll-vection during exposure to stimuli rotating around the line of sight, while varying the object density in the fore- and background. Results showed that, as expected, the density interacted with the fore- and background segregation in the modulation of both postural sway and roll-vection. Based on these results, we concluded that the ratio between the densities of the fore- and background patterns is an important factor in the interaction with the fore-background segregation, and not the density of the rotating pattern per se. More specifically, when a rotating background contained more objects (to a certain maximum) than the static foreground a larger visual-vestibular conflict was evoked, resulting in longer vection and more postural sway, compared to a rotating foreground with more objects than the static background. Finally, the finding that postural sway, as well as vection were modulated in a similar way, provided new evidence for a common neural origin regulating both postural sway and vection.

Table 8.1 on the next page provides an overview of the research questions, examined variables and significant findings reported on in **Chapters 2 to 7**.