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Adaptation to virtual prisms and its relevance for neglect rehabilitation: a single-blind dose-response study with healthy participants

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ABSTRACT

Prism adaptation (PA) has been applied with mixed success as a rehabilitation method of spatial neglect. Results from many single-case and multiple case studies as well as randomized controlled trials do not produce a clear picture of the efficacy of PA. We here tested a new method of PA, by inducing adaptation effects in the virtual reality. Healthy participants were attributed to one of four groups: no deviation, 10-, 20-, or 30-degrees rightward deviation. In contrast to classical wedge prisms, we induced the visual shift progressively. Participants performed two variants of the bisection and the landmark task to measure cognitive transfer of adaptation effects. Pointing error was directly related to the degree of optical deviation, and was greatest immediately following adaptation. Transfer was only observed in the bisection tasks, and only in the 30-degrees group. Due to the gradual induction of the spatial deviation the majority of participants were unaware of the adaptation effects. These findings show that large rightward deviation may affect sensorimotor performance in healthy participants similarly to neglect patients. Moreover, the finding that only participants adapted to 30-degrees showed biased bisection performance suggests that a critical threshold must be reached in order to induce significant visuomotor transfer.

Keywords: Spatial neglect; line bisection; visual attention; prism adaptation; rehabilitation.

INTRODUCTION

The rehabilitation of spatial neglect is a challenging topic. Neglect is a severe and pervasive disorder, it affects motor recovery negatively and is associated with lower post-stroke functional independence in activities of daily life (Buxbaum et al., 2004; Denes, Semenza, Stoppa, & Lis, 1982; Kalra, Perez, Gupta, & Wittink, 1997; Ptak & Fellrath, 2013). There is a manifest need for simple and cost-effective rehabilitation techniques that may be adjusted to different settings and be used with patients showing variable levels of deficit (Barrett, Goedert, & Basso, 2012; Kerkhoff & Schenk, 2012). Adaptation to right-deviating prisms appears to offer an efficient tool that can be applied repeatedly and in short sessions. Prism adaptation (PA) relies on the mismatch between the perceived position of a target seen through the prismatic goggles and its real position relative to the body. After noticing the error the observer performs a corrective movement in the opposite direction, which may be quantified after PA by asking him to point to a target with eyes closed.

Following an early report suggesting that the adaptation effect may affect the spatial bias of neglect patients up to two hours after PA (Rossetti et al., 1998) several experimental and observational studies reported beneficial effects in classic neglect measures (Frassinetti, Angeli, Meneghello, Avanzi, & Làdavas, 2002; Ladavas, Bonifazi, Catena, & Serino, 2011; Serino, Barbiani, Rinaldesi, & Ladavas, 2009), as well as more specific symptoms, such as gaze exploration bias (Angeli, Benassi, & Ladavas, 2004; Ferber, Danckert, Joanisse, Goltz, & Goodale, 2003), visual search (Saevarsson, Kristjansson, Hildebrandt, & Halsband, 2009), mental imagery (Rode, Rossetti, & Boisson, 2001) or postural imbalance (Tilikete et al., 2001). However, initial negative reports (Morris et al., 2004; Rousseaux, Bernati, Saj, & Kozlowski, 2006) called for more stringent tests of the efficacy of the method, which can only be provided by randomised controlled trials (RCTs). Unfortunately, although several RCTs have been published, the evidence supporting a systematic use of PA for neglect rehabilitation remains equivocal. Three trials reported a significant advantage of neglect patients treated with PA (total N = 51) as compared to a placebo control group, in a series of neglect measures (Serino et al., 2009; Vaes et al., 2016) or a functional independence scale (Mizuno et al., 2011). Two studies observed comparably positive effects of PA and visual scanning training, both interventions being provided at the same intensity (Priftis, Passarini, Pilosio, Meneghello, & Pitteri, 2013; Spaccavento, Cellamare, Cafforio, Loverre, & Craca, 2016). By contrast, one study described mixed results, as patients treated with PA showed greater improvement than controls after treatment, but group results were indistinguishable after one month (Nys, de Haan, Kunneman, de Kort, & Dijkerman, 2008). More disappointingly, no effects additional to spontaneous recovery were measured by four studies that included a total number of 72 patients treated with prisms (Mancuso et al., 2012; Rode et al., 2015; Ten Brink et al., 2017; Turton, O'Leary, Gabb, Woodward, & Gilchrist, 2010). In addition, some positive findings are not really compelling and raise the question of their clinical relevance. For example, in the study by Nys et al. (2008) patients showed a reduction of their bias in line bisection of ~1-2%, and the effect of PA in activities of daily life in the study by Mizuno, et al. (2011) was only found in patients with mild neglect.

One may conclude that this divergence of findings simply reflects the variability of symptoms associated with spatial neglect, or that the gains that can be obtained from PA are essentially random. However, at closer look several factors emerge that may systematically contribute to the outcome of PA rehabilitation. First, PA may affect visuomotor performance more than purely perceptual measures (Ptak, 2017; Striemer & Danckert, 2010b). For example, PA was found to improve performance in the classic line bisection task, but not in the landmark task (Harvey, Milner, & Roberts, 1995), which requires judging the accuracy of line pre-bisections (Striemer & Danckert, 2010a). In addition, patients with motor-intentional or 'aiming' deficits appear to benefit more from PA than patients with purely perceptual deficits (Fortis, Chen, Goedert, & Barrett, 2011; Goedert, Chen, Boston, Foundas, & Barrett, 2014). These findings agree with Redding & Wallace's (2006) proposal that the main mechanism responsible for PA effects in neglect patients is the leftward recalibration of the coordinates of a motor-sensory reference frame.

A second observation is that PA effects may depend on the degree of spatial error induced by the prisms. Some authors have called for studies evaluating the dose-response to prisms of different deviating powers (Barrett et al., 2012). Indeed, Facchin, Beschin, Toraldo, Cisari & Daini (2013) found that the aftereffect was maximally 33% of the angular deviation of the prisms, and that in neglect patients prisms with a greater number of dioptres induced the largest effects. Similarly, the effect of PA on line bisection judgments in healthy participants was shown to depend on the degree of deviation (Michel & Cruz, 2015). Small deviations may thus fail to produce transfer to other tasks because the size of the adaptation effect is too small to be of any significance. Unfortunately, there is an optical limit to the technology, as wedge prisms with more than 20 dioptres not only displace the field of view, but also add optical aberrations and may produce significant discomfort.

Third, whether transfer effects from PA are found depends on the direction of the spatial deviation. While neglect patients benefit from prisms with *rightward* deviation healthy controls show transfer to visuospatial tasks only when they are adapted with *leftward* deviating prisms (Michel, 2016; Schintu et al., 2017). However, to induce neglect-like behaviour in healthy participants is not the same as alleviating neglect with PA in stroke patients. It is therefore unclear to what extent the induction of such neglect-like bias in controls can be considered a good model of PA effects in neglect patients. The reason for the absence of cognitive transfer effects after rightward deviation in healthy participants is unknown, but one possibility is that effects may only appear with optical deviations that are comparatively larger than when leftward deviating prisms are used.

A final question concerns adequate blinding, which is a major concern for rehabilitation studies. Several of the RCTs cited above were performed using a single-blind design, where patients either underwent PA or performed pointing movements with non-deviating goggles. However, even if patients are blind about the type of goggles they are wearing and their reports suggest no awareness of the optical deviation (Rode et al., 2015), the compensation (and thus, the aftereffect) relies on the perception of the mismatch between target and hand position. The PA technology thus precludes complete blinding of subjects.

We addressed these points in an experimental study on healthy participants, by using virtual reality as an alternative to wedge prisms. In a virtual environment different degrees of spatial error between hand and target can be induced without any discomfort for the participant. In addition, the mismatch can be induced progressively, which makes it difficult for the subject to become aware of the manipulation. By making use of these advantages of ‘virtual prisms’ we tested whether rightward optical deviations of up to 30 degrees affect manual and perceptual judgments in healthy participants.

MATERIALS AND METHODS

Participants

Forty-eight healthy subjects (34 women, mean age 22.8 ± 3.3 years) participated to the study. Forty-three participants were classified as right-handers and five as left-handers based on scores in the Edinburgh Handedness Inventory (Oldfield, 1971). None of them had motor disorders and all had normal vision. The sample size was determined through power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) for repeated-measures designs, assuming a medium effect size ($\alpha = .05$; $\beta = .8$; $\eta^2 = .06$). The power analysis for our 4 x 2 design predicted a total sample size of 48. Participants were randomly assigned to one of four groups (12 participants per group), defined by different degrees of optical deviation during adaptation: 0 (no deviation), 10, 20 or 30 degrees of deviation. One subject was replaced due to a technical error. All participants gave informed consent, and the study was approved by the ethical commission of the canton of Geneva.

Stimuli and procedure

A Vive VR system (HTC Corp., Taoyuan, Taïwan) was used to present the stimuli and induce an optical shift during adaptation. Participants were seated while wearing the VR headset and asked to hold a controller in their right hand. The controller had a button similar to a gun trigger, and its position was tracked in real-time by the system and reproduced in virtual space. The VR headset had a field of view of 110 degrees at a refresh rate of 90 Hz, and the system was calibrated so that the origin of the of three-dimensional virtual space was aligned with the midline of the subjects’ trunk. In order to induce adaptation effects the 3D-coordinates of the controller were modified by adding a fixed amount of degrees in the xz-plane, so that the image of the controller appeared radially displaced by 10, 20 or 30 degrees rightward from its real position. It should be noted that the principle of adaptation when using virtual reality is slightly different from that of wedge prisms. In contrast to virtual reality wedge prisms affect the entire visual field (including the pointing target), shifting it in one direction. Since participants only see their hand in the end part of the pointing movement they initially aim toward the perceived (i.e., shifted) target position and only correct their movement once their hand becomes visible through the goggles. In virtual reality subjects never see their arm, but a representation of the controller. In addition, the pointing target only exists in the virtual space, and its *perceived* position is always its *real* position. A shift of the target position therefore does not create a mismatch between hand and target. In order to induce adaptation effects we shifted the perceived position of the controller relative to its real position. However, given that the controller is always visible, when using large deviations subjects might become aware that the location at which it is shown does not correspond to the real (proprioceptive) position of their hand. For this reason, rather than inducing it instantaneously we increased the shift incrementally in small steps while subjects were performing pointing movements.

Each subject participated to one experimental session, consisting in: testing before adaptation (baseline), adaptation, testing after adaptation and recalibration. Each of the four phases was followed by a test of open-loop pointing as measure of the adaptation effect (open-loop pointing before recalibration was performed in order to measure the decay of sensorimotor adaptation effects). All tasks were performed with the dominant hand. At the end of the experimental session, the subjects were asked to complete a questionnaire assessing their awareness of pointing performance and target deviation.

Adaptation and recalibration

Adaptation. Subjects saw the projection of 3 x 3 black spheres in front of them and approximately at arm length (~70 cm) in virtual space (Figure 1A). The image of the controller was replaced with the image of a white rod. No stimuli or cues other than the nine spheres and the virtual rod were visible. At the beginning of each trial, one of the spheres turned red, and the participant was instructed to touch it with the virtual rod as quickly as possible. The position of the red sphere varied randomly across 100 trials. During pointing, a progressive visual shift of the controller position was induced: at the onset each subject saw the virtual rod at the position corresponding to the real position of the controller, which was also the position of their hand (0 degrees deviation). Across two minutes (i.e., approx. 50-70 pointing movements) its position gradually shifted by a small amount to the right until it reached the desired displacement of 10, 20 or 30 degrees of visual angle (depending on the group to which participants were assigned). Hence between two successive trials the position of the virtual rod moved rightward only in very small steps (~0.15 - 0.5 degrees per trial). This procedure allowed us to induce a deviation without the subjects noticing it (see results of the awareness questionnaire).

Recalibration. Recalibration was identical to adaptation, except that no visual shift was induced and all four groups thus pointed with 0 degrees deviation.

Figure 1 about here

Adaptation and transfer effects

Effects of adaptation were evaluated with open-loop pointing at four different time-points. Transfer effects were examined with two variants of the line bisection task (line bisection and space bisection) and two variants of the landmark task (line landmark and space landmark). These four variants were used in order to dissociate sensorimotor transfer (which should be observed in line and space bisection) from perceptual transfer (observed in both landmark tasks). In addition, lines and spaces were used to test within-object coding (present in the line bisection and line landmark tests) and space-based coding (present in the space bisection and space landmark tasks). The four bisection tasks were performed in random order.

Open-loop pointing. A black dot (2.6 degrees of visual angle) was projected exactly in front of the subject, centred on her/his sagittal midline. The virtual environment showed a monotonous white space and was therefore devoid of any cues that could bias open-loop pointing. Visibility of the controller was turned off and subjects did not see their body or arms, so that there was no visual feedback about performance. The subjects were asked to hold the controller at chest height (start position), to reach toward the target and to press the controller button. The trial was repeated 5 times for each evaluation.

Line bisection. Participants were asked to bisect a series of black lines presented in a completely white virtual environment. Lines were projected at a distance of 50 cm in front of the subject, centred on the body midline. They were 35, 50 or 65 degrees of visual angle, and their width was 1.15 degrees. The controller was visible and projected a red light from its tip that subjects directed at the line in order to ‘cut through’ it at its estimated midpoint (Figure 1B). Participants performed four trials for each line length for a total of 12 trials.

Space bisection. The task was identical to the line bisection task except that instead of the line only two vertical lines (length: 11.4 degrees of visual angle) were visible as delimiters of the left and right border of a space that should be bisected.

Line landmark task. The stimuli were identical to the line bisection task, except that a red vertical mark (length: 11.4 degrees) bisected the line either in its centre or displaced by 2, 4, 8, or 16% of the total line length to the left or right of the centre. Participants were asked to indicate whether the bisection mark was bisected in the centre or to the left or right. There were 9 trials for each line length, resulting in a total of 27 trials.

In order to evaluate the subjective centre in numerical terms we calculated a subjective bias score, computed as follows: zero was assigned every time the subject's answer was correct. An error was coded numerically by assigning a score that represented the degree of deviation of the bisecting line. For example, when the subject said ‘centre’ or ‘right’ for a line that was bisected at -2%, a value of +2 was assigned to this trial, while for a line bisected at +4% a value of -4 was given. The subjective bias was computed as the median of all scores obtained from the 27 trials, by excluding trials in which the line was bisected in its centre. A positive bias indicated that the subjective centre was shifted to the right (i.e., that the left side was perceived as longer), while a negative bias indicated a shift toward the left.

Space landmark task. The task was identical to the line landmark task except that only the borders of a delimited space (as in the space bisection task) as well as the bisection mark were shown.

Awareness questionnaire

The awareness questionnaire aimed to assess participants’ perception of the mismatch between the reach targets in the adaptation task and the controller as well as their awareness of visuomotor adaptation effects. It started with an open question probing any awareness of the visual shift (‘Did you feel something strange or bizarre when you were reaching for the spheres? If yes, could you describe it?'). The following questions assessed awareness of adaptation more directly and was composed of a series of questions about the open-loop pointing task that had to be rated on a five-point Likert scale ranging from 'strongly agree' to 'strongly disagree '(e.g., 'I felt that my hand did not aim towards the target').

RESULTS

Open-loop pointing

Figure 1 shows pointing errors in open-loop pointing across the four time points. A mixed ANOVA with group (0, 10, 20, 30 degrees) as between factor and time (baseline, adaptation, decay, recalibration) as within factor revealed a significant effect of group [F (3,44) = 8.99, $p < .001$, $\eta^2 = .380$] and time [F (3,44) = 178.24, $p < .001$, $\eta^2 = .802$] as well as a significant group X time interaction [F (9,44) = 30.21, $p < .001$, $\eta^2 = .673$). A series of one-way ANOVAs with the factor group on each time-point of measure showed a significant effect after adaptation [F (3,44) = 39.47, $p < .001$, $\eta^2 = .729$] and after decay [F (3,44) = 8,49, $p < .001$, $\eta^2 = .367$], but not at baseline [F (3,44) = .69] and after recalibration [F (3,44) = .12]. Bonferroni contrasts revealed that after adaptation the leftward bias of each group differed significantly from the other groups (all $p < .05$), except for the comparison of 30- with the 20-degrees group ($p = .067$). After decay the 30-degrees group still exhibited a significantly greater leftward bias than the 10- and the 0-degrees group ($p < .01$), but no other comparison reached significance.

Figure 2 about here

Transfer effects

Line and space bisection. Figure 2 shows the effects of adaptation in the two bisection tasks and the two landmark tasks. A mixed ANOVA on the line bisection data with group as between factor and time (pre, post) as within factor yielded a significant effect of time [F (1,44) = 5.32, $p < .05$, $\eta^2 = .108$] and a significant group X time interaction [F (3,44) = 3.30, $p < .05$, $\eta^2 = .184$] whereas the group effect was not significant [F (3,44) = .29]. In order to follow up the group X time interaction we performed paired t-tests for each group, comparing bisection bias at baseline and after adaptation. These comparisons showed a significant pre-post difference only in the 30-degrees group [t (11) = 2.59, $p < .05$].

Very similar results were obtained in the space bisection task (Figure 2). There was a significant time effect [F (1,44) = 5.80, $p < .05$, $\eta^2 = .117$] and a marginally significant group X time interaction [F (3,44) = 2.80, p = .051, $\eta^2 = .160$], but no main effect of group [F (3,44) = .26]. Again, only the 30-degrees group had a significant leftward shift on bisection in the pre-post comparison [t (11) = 2.9, $p < .05$].

Line and space landmark tasks. As for bisection tasks the data were analysed with mixed ANOVAs with factors group and time. The line landmark task did not yield any significant effects (group [F (3,44) = .41]; time [F (1,44) = 2.16]; group X time [F (3,44) = .82]). In the space landmark task a trend toward significance was found for the effect of time [F (1,44) = 3.15, p = .083, $\eta^2 = .067$] indicating that the subjective bias was larger (i.e., shifted to the right) following adaptation compared to baseline. Neither the main effect of group [F (3,44) = 1.31] nor the group X time interaction [F (3,44) = 0.28] reached significance.

Task correlations: Table 1 shows a correlation matrix for open-loop pointing and transfer effects. Consistent with the factorial analyses the adaptation effect evaluated through open-loop pointing predicted the pre-post difference in both bisection tasks, but not in the landmark tasks.

Table 1 about here

Awareness questionnaire

Only 3 subjects in the group with 30 degrees bias perceived a visual shift between the controller and pointing target during the adaptation phase, but they did not report any awareness of hand deviation during open-loop pointing. None of the remaining subjects reported any awareness of deviation. Though the number of aware subjects was too low to allow a statistical analysis, it is interesting to note that their pre-post difference in the two bisection tasks was lower (line: 1.22; space: 2.3) than of the unaware subjects of the 30-degrees group (line: 4.36; space: 5.13).

Figure 3 about here

DISCUSSION

Our findings clarify a number of points concerning PA effects observed in previous studies and provide a methodological expansion by reproducing adaptation effects in the virtual reality. We here discuss our finding that robust PA effects may only be induced by large deviations, effects of virtual prisms on visuomotor versus purely perceptual measures and finally comment on several methodological advantages of virtual as compared to wedge prisms.

Though increasing deviations lead to greater aftereffects, the relation between prism power and the size of the aftereffect was not linear. When relating the size of the aftereffect (i.e., the difference between pre- and post-bias in open-loop pointing) to the degrees of prism deviation we obtain values of 33%, 38% and 46% for 30-, 20- and 10-degrees deviations. These decreasing aftereffects for increasing prism power do not correspond to the observations by Facchin et al. (2013) who tested the effects of prisms deviating by 2.9, 5.7 or 8.5 degrees in patients with spatial neglect. In their study, aftereffects were greatest for the prisms of greatest power (33%) and smallest for the 2.9 degrees prisms (14%). The differences might be due to a combination of the strength of sensorimotor adaptation effects induced by prisms (very small deviations might induce only small or no aftereffects) and biomechanical constraints, which make it difficult to make movements further to the left with increasing angle of the right arm from the body midline.

If, as suggested by Redding & Wallace (2006), PA leads to recalibration of a biased sensorimotor reference frame, the bias induced by PA should be directly related to the size of transfer effects. Though some previous studies attempted to establish such a correlation (e.g., Frassinetti et al., 2002), this has not been done systematically. We here found that the bias in open-loop pointing was a significant predictor of the leftward bias in bisection. However, our findings also indicate that transfer effects are not linearly related to prism power, but are absent up to deviations of 20 degrees, and only appear at 30 degrees. This finding suggests that the aftereffect has to reach a critical threshold below which PA is not beneficial for other visuomotor tasks. Though the existence of such a critical threshold requires confirmation it opens up new possibilities to interpret previous positive as well as negative findings. For example, given the high variability of intraindividual and interindividual performance observed in neglect patients, adaptation effects induced by prisms with low power may be too small to produce transfer to visuomotor tasks. In a patient sample selected for study some patients may thus show aftereffects of sufficient size, while in others the aftereffect may be insufficient to cause transfer. The fact that the critical threshold can only be reached with prisms of high power may explain the absence of positive effects reported in some previous studies (e.g., Turton et al., 2010). The possibility that an individual critical threshold has to be reached in order for PA to work calls for within-subject studies on healthy subjects as well as dose-response studies including patients with neglect.

A second important finding of our study was that transfer effects were only observed in two variants of the bisection task, but not in the Landmark task. The difference between both tasks is that only the classic bisection task requires the activation of a motor program. Though the finding disagrees with modulations of Landmark performance in healthy subjects after leftward PA (Michel & Cruz, 2015; Schintu et al., 2017; Schintu et al., 2014) it agrees with results of Striemer & Danckert (2010a), who observed a very similar pattern in patients with neglect. An interesting single-case dissociation supporting the distinction between sensorimotor and purely perceptive effects was also reported by Ferber et al. (2003). Following PA their neglect patient produced increased numbers of saccades toward the left side of space, yet remained unaware of stimuli presented on this side. Together, these observations support the proposal that PA effects are essentially sensorimotor and do not imply neural systems involved in visual perception and awareness (Newport & Schenk, 2012; Striemer & Danckert, 2010b). Additional evidence suggesting that recalibration following PA is motor, and not perceptive, comes from studies showing that patients with motor-intentional neglect benefit more from PA than patients with predominantly perceptual neglect (Goedert et al., 2014). However, these effects require further confirmation as some studies have found significant effects of PA on purely perceptual tasks, such as the Landmark task in healthy participants (Schintu et al., 2017) and reading (Angeli et al., 2004; Farne, Rossetti, Toniolo, & Ladavas, 2002; Priftis et al., 2013) or mental imagery (Rode et al., 2001) in patients with neglect. PA studies should thus systematically distinguish between motor and perceptual measures and between patients suffering from motor-intentional versus perceptual neglect (Bisiach, Ricci, Lualdi, & Colombo, 1998). This requires the development of tests that clearly distinguish between both components, as most classic clinical tests used to evaluate the outcome of neglect therapy rely on a mixture of sensorimotor and visual-perceptual mechanisms.

An important aspect of our study is that we used rightward deviating prisms and yet found significant adaptation and transfer in healthy participants. This is in strong contrast to previous studies using wedge prisms, which induced neglect-like spatial biases in healthy controls, but only when using leftward deviating prisms (Michel & Cruz, 2015; Schintu et al., 2017; Schintu et al., 2014; Striemer, Russell, & Nath, 2016). Interestingly, all previous null results after rightward adaptation were obtained with prisms of smaller power (most often, 10-15 degrees), which is coherent with the absence of transfer effects in subjects adapted with deviations below 30 degrees. The large deviations of virtual prisms thus provide the possibility to study in healthy participants PA-induced transfer effects that are comparable to those observed in neglect patients.

Compared to traditional therapy using wedge prisms, PA using virtual reality provides several important advantages. First, the methodology allows for better controlled blinding of participants. Though three of our participants (all three in the group with the most extreme deviation) reported some awareness of the deviation, none was aware that her/his pointing movements were directed further leftward after, compared to before PA. Healthy subjects adapted with wedge prisms often spontaneously express surprise when realizing that they are not aiming straight toward the target (Rode et al., 2015). While neglect patients appear to be unaware of the adaptation, they must nevertheless be aware of the displacement of their hand when seen through the prismatic goggles, otherwise they would be unable to correct their movement. We circumvented this drawback by inducing the spatial bias gradually. Such gradual induction is impossible with wedge prisms, but easy to program in the virtual reality, thus offering the possibility to plan single-blind or even double-blind clinical trials.

A second advantage to wedge prisms is that the virtual environment we used was devoid of any external cues that could bias pointing movements performed during adaptation and measures of post-adaptation effects. When using classic prisms, stimuli are presented on sheets of paper that are placed on a table, which provide additional reference points that may affect pointing.

The most important advantage is that the power of virtual prisms can be increased progressively and to much more extreme deviations than wedge prisms. Perceptual aberrations and discomfort are therefore eliminated and the visual environment is comparable for different deviation conditions. Virtual prisms can therefore be adjusted individually to provide tailored therapy for neglect patients.

The aim of our study was to test the possibility that virtual prisms can be used as an alternative to traditional wedge prisms, but it leaves several questions open. First, participants were not resting, but performed the bisection and landmark tasks between adaptation and the measure of decay, which might have affected the speed of decay (Striemer & Danckert, 2010a). Though the decay of adaptation effects cannot be considered spontaneous, it was surprisingly rapid. This suggests that the neural systems involved in PA effects exhibit a high degree of dynamic plasticity, allowing for rapid adaptation and recovery. Second, while we measured adaptation effects in the virtual environment we did not test whether they transfer to reality (e.g., paper-and-pencil tasks). This leaves open the possibility that subjects experienced a misalignment between their hand and the virtual rod, and then applied the same degree of misalignment in open-loop pointing. This explanation remains possible though unlikely given the subjects' lack of awareness of the deviation during adaptation and open-loop pointing. Third, we were not able to show prolonged maintenance of the adaptation effects with smaller as compared with larger deviations (Facchin et al., 2013). It is possible that the gradual induction of adaptation in our study was responsible for the short-lived nature of adaptation effects, as participants trained only a short time with the maximal deviation. Future work should therefore attempt to decrease the speed of decay, either by prolonging adaptation or by adapting repeatedly in short sessions. Studies with healthy participants (Schintu et al., 2014) and neglect patients (Frassinetti et al., 2002) have shown that repeated PA may lead to prolonged maintenance of adaptation effects, and similar findings may be expected with virtual prisms. Another question is whether transfer effects in healthy participants may be achieved with other visuomotor tasks than line bisection (for example visual search, Ricci et al., 2016). Further, our findings show that performance in line and space bisection is highly correlated, suggesting that both tasks rely on highly similar mechanisms (Pedrazzini, Schnider, & Ptak, 2017). Nevertheless, the findings raise the question whether PA may affect space-based processing to a different degree than object-centred mechanisms. Finally, neglect is a heterogeneous disorder that may affect attentional, representational or motor aspects relatively independently. Our findings address the contrast between perceptual and visuo-motor aspects of performance and are therefore possibly limited to perceptive tasks in the peripersonal space. Whether virtual PA applies only to specific measures of performance or specific subtypes of neglect, and whether it may affect everyday life activities of neglect patients remains to be examined.

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Table 1. Pearson correlations between the open-loop (OLP) measure taken just after adaptation and the size of the bias on line bisection and landmark task (difference pre-post adaptation). Significance levels are indicated with ** (p < .01) and * (p < .05).

	OLP	Line bisection	Space bisection	Line landmark
Line bisection	**-.39****			
Space bisection	**-.35***	**.61****		
Line landmark	.2	-.05	-.01	
Space landmark	-.14	.09	.12	.01

Figure legends

Figure 1. A) Adaptation task. Participants touched the sphere that turned red (here shown in light grey). Instead of the controller, the image of a wooden rod was visible. B) Line bisection task. Note that in all tasks the arm of the subject was invisible.

Figure 2. Error in open-loop pointing measured at baseline, after adaptation, after decay and after recalibration (error bars show corrected standard error according to Cousineau & O'Brien, 2014).

Figure 3. Subjective bias on the four transfer tests before and after adaptation. A) Line bisection, B) Space bisection, C) Line landmark, D) Space landmark.

Figure 1

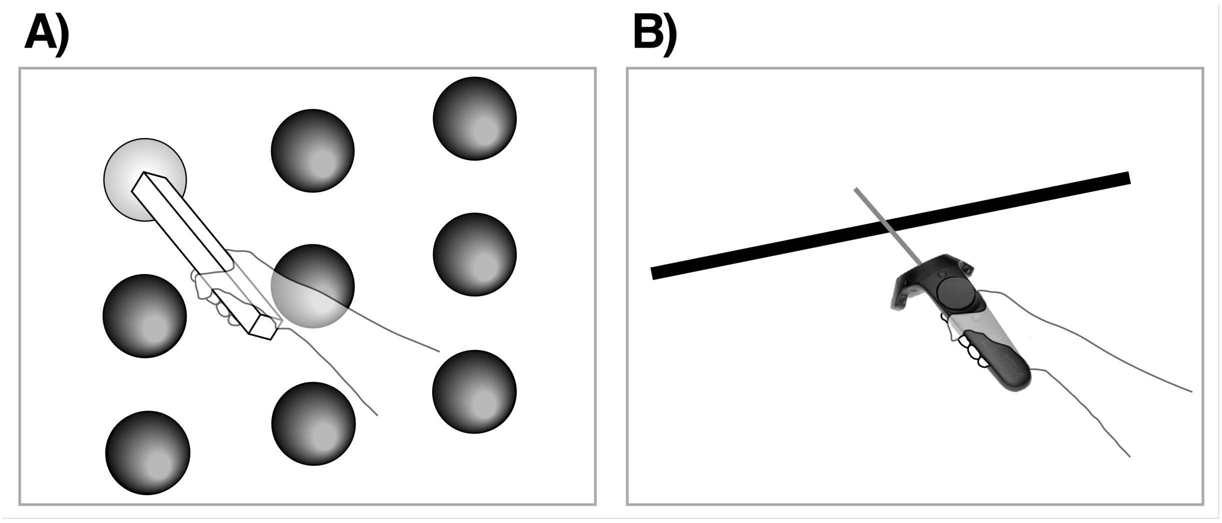


Figure 2

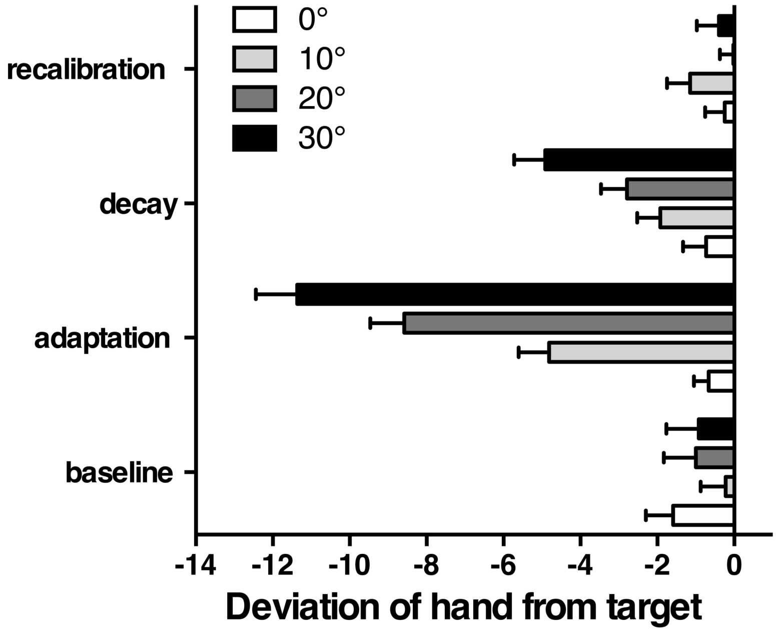
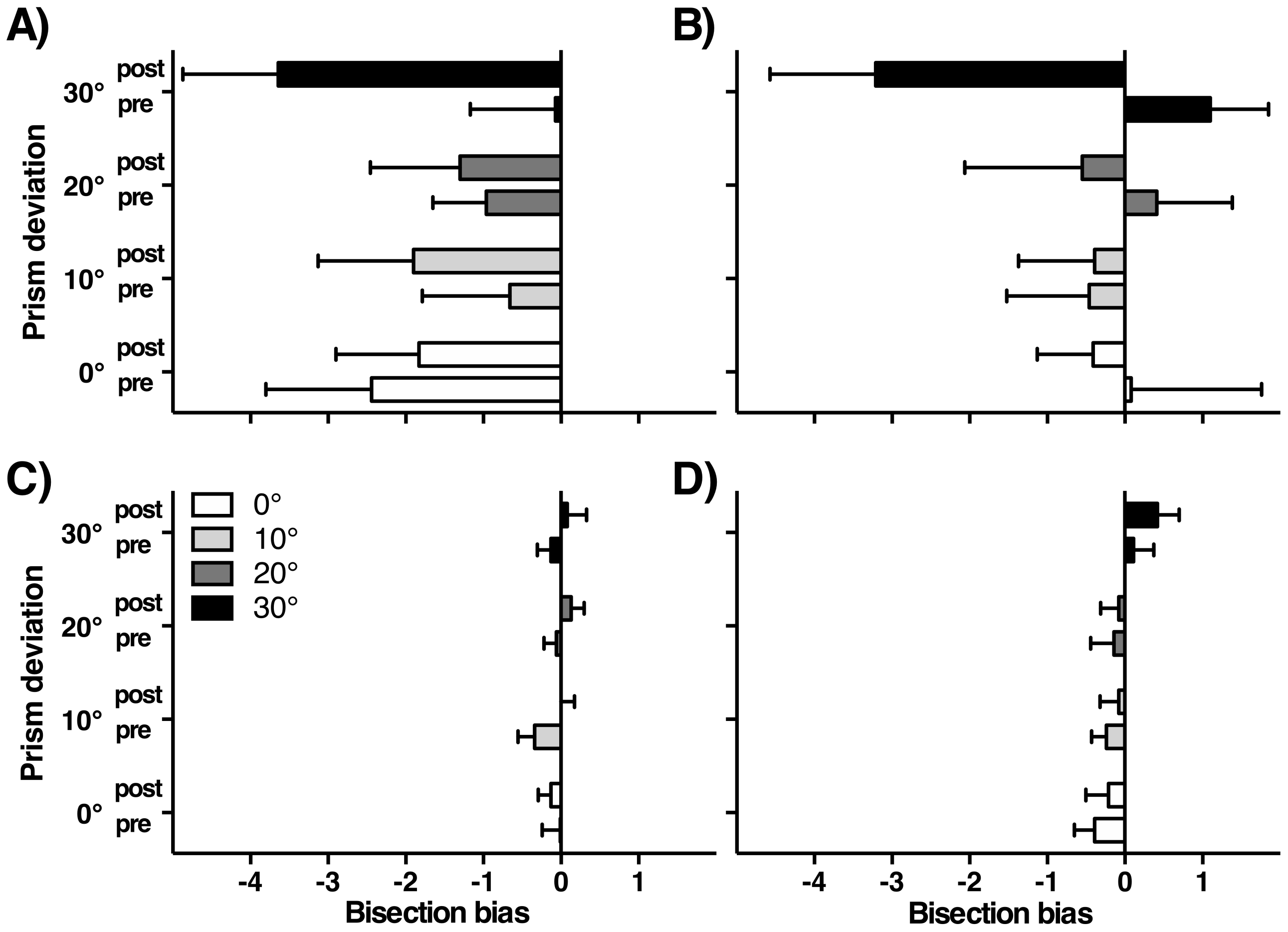

0°
10°
20°
30°
recalibration
decay
adaptation
baseline
-14
-12
-10
-8
-6
-4
-2
0
Deviation of hand from target

Figure 3


A)
B)
C)
D)
Prism deviation
30°
20°
10°
0°
post
pre
0°
10°
20°
30°
-4
-3
-2
-1
0
1
Bisection bias