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Editorial

Prism adaptation: From rehabilitation to neural bases, and back

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Prism adaptation rehabilitation for spatial cognition disorders has been explored since 1998 and a wave of prism adaptation research grew in clinical and basic science fields. A special issue of Cortex is devoted to this topic, which illustrates how translational research does not always work from workbench to bedside. Over the last 20 years prism adaptation has spread backward from the rehabilitation of unilateral neglect (McIntosh, Rossetti, & Milner, 2002; Rode et al., 2006a; Jacquin-Courtois, Rode, Pisella, Boisson, & Rossetti, 2008, 2010) to the exploration of the link between sensorimotor adaptation and healthy attentional processes (Colent, Pisella, Bernieri, Rode, & Rossetti, 2000; Michel et al., 2003a; Michel, 2006, 2016), body schema and reference frames (Girardi, McIntosh, Michel, Vallar, & Rossetti, 2004; Michel, Rossetti, Rode, & Tilikete, 2003b) and high level cognitive processes (e.g., Jacquin-Courtois et al., 2010; Rossetti et al., 2004). And parallel explorations led to the clinical use of prism adaptation to improve chronic pain (e.g., Christophe et al., 2016; Sumitani et al., 2007) or constructional disorders (Rode, Klos, Courtois-Jacquin, Rossetti, & Pisella, 2006b).

Uncovering the promising therapeutic usage of prism adaptation has given rise to numerous explorations in patients as well as clinical trials (Frassinetti, Angeli, Meneghello, Avanzi, & Làdavas, 2002; Shiraishi, Yamakawa, Itou, Muraki, & Asada, 2008; Serino, Barbiani, Rinaldesi, & Làdavas, 2009; Mizuno et al., 2011; Rode et al., 2015; Ten Brink, Visser-Meily, & Nijboer, 2015, 2017). It also boosted the need for understanding their mechanism of action at both the sensori-motor level (Harris 1963; Gaveau et al., 2018, 2014; Hatada, Miall, & Rossetti, 2006; Inoue, Uchimura, & Kitazawa, 2016; Michel, Pisella, Prablanc, Rode, & Rossetti, 2007; Nijboer et al. 2008; O'Shea et al., 2017, 2014; Uchimura & Kitazawa, 2013) and their expansion to the cognitive level (e.g., Nijboer, Nys, van der Smagt, van der Stigchel, & Dijkerman, 2011; Rossetti et al., 2004; Rossetti et al., 2015). Despite of this blossoming rise of interest for prism adaptation, we lack empirical evidence and consensus on several important issues. First we need to better understand the basic mechanisms of adaptation and how (conscious *vs* unconscious, which threshold) and which errors (dynamic movement feedback, terminal errors) can feed back into the adaptive system (Gaveau et al; 2018; Hanajima et al. 2015). Second, the diverging results of clinical trials points to the need to clarify which patient may respond to which adaptation protocol and whether all patients may benefit from prism adaptation. Adaptation protocols used in the clinic vary in term of optical shift generated by prisms (from 5 deg to 20 dioptres), in terms of daily (1 or 2) and weekly dosage (from 1 to 10), total duration (1 day to several weeks) and number of adaptation sessions as well as in terms of activities performed during prism exposure (boring laboratory pointing task to ecological games of activities). Crucially they also vary in terms of sensori-motor adaptation assessment (none, proprioceptive shift or visual-proprioceptive realignment). A flourishing methodological arsenal has been recently invoked to explore the mechanisms of prism adaptation: PET, fMRI, TMS, paired-pulse TMS, tDCS, magnetic resonance spectroscopy and EEG have been used in combination with behavioural variables to identify elementary processes and neural circuits solicited by prism

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adaptation. The initial claim that prism adaptation may restore the interhemispheric balance in neglect patients has not received consensual support from these experimental studies and further and more systematic explorations are needed to offer the opportunity to produce a comprehensive view of the rich network that seems to be affected by prism adaptation. The emergence of integrated models of prism adaptation (Inoue et al., 2016; Petitet, O'Reilly, & O'Shea, 2018) is especially expected for optimal clinical applications of this deceptively simple technique.

The Cortex special issue aims at collecting up-to-date theoretical and empirical contributions to blaze the future trails of prism adaptation research. Future contributions in the field should address the following main issues: clarifying terminology, exploring the precise physiological mechanisms of sensori-motor adaptation and their neural network implementation, the peculiar expansion of prism adaptation to spatial cognition and attentional parameters. These explorations and modelling of the available corpus of data should help understanding the pathophysiology of therapeutic mechanisms of prism adaptation far beyond the sensorimotor and reference frame level (Jeannerod & Rossetti, 1993), to predict which patients should respond to this technique (e.g., Goedert, Chen, Foundas, & Barrett, 2018), and to envisage which other pathological conditions may benefit from prism adaptation (Jacquin-Courtois et al., 2013).

Terminology is a key tool for the mind to grasp empirical observations and to elaborate realistic models of the underlying mechanisms. Over the last century the terminology used to describe prism adaptation methods, observations and concepts has remained loosely defined and fluctuating. Attempts to clarify this terminology (e.g., Kornheiser 1976; Welch 1986; Redding, Rossetti, & Wallace, 2005; Bastian, 2008) has remained insufficiently effective and more efforts are needed to develop a consensual glossary in the field. A more detailed dissection of prism adaptation methodology and a more precise terminology will be required in order to outline conceptual and methodological issues and accurately dissect components and consequences of prism adaptation.

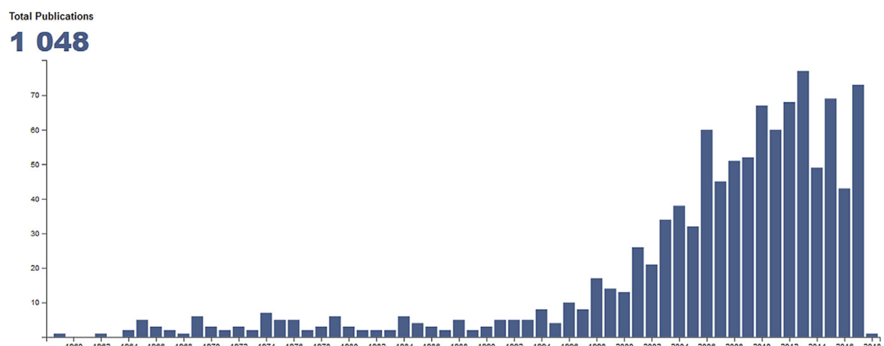
Exploring the precise mechanisms of prism adaptation has become a growing issue for several reasons. First clinical applications of prism adaptation have raised the need for a better understanding of this deceptively simple intervention (e.g., Barrett, Goedert, & Basso, 2012; Bastian, 2008; Milner & McIntosh, 2005; Redding et al., 2005; Striemer & Danckert, 2010). Second, new technologies have also begun to address the mechanisms of sensori-motor learning and adaptation (e.g., Darainy, Vahdat, & Ostry, 2013; Hertzfeld et al., 2014), although the boundary between these two mechanisms has remained insufficiently outlined. In-depth analysis of error signals and behavioural consequences of prism exposure allow for refined understanding of this type of sensori-motor adaptation (e.g., Gaveau et al., 2018, 2014; O'Shea et al., 2014; Uchimura & Kitazawa, 2013; Inoue et al. 2015).

Specifying the neural networks involved in prism adaptation is not only necessary to improve our knowledge about brain plasticity (e.g., Bastian, 2008; Pisella, Rode, Farnè, Tilikete, & Rossetti, 2006) but also aims at better predicting the individual patient's responsiveness to prism adaptation (e.g., Crottaz-Herbette et al., 2017; Goedert et al., 2014, 2018; Ronchi, Rossi, Calzolari, Bolognini, & Vallar, 2018; Ten Brink et al., 2017). Recent neuronal recording (e.g., Inoue et al., 2016; Inoue & Kitazawa, 2018), brain stimulation (Panico, Sagliano, Grossi, & Trojano, 2016, 2017, 2018; Schintu et al., 2016; O'Shea et al., 2018), electrophysiological recordings (Martín-Arévalo et al., 2016) have brought more original insight and more innovative views of prism adaptation circuitry (Inoue & Kitazawa, 2018) than traditional functional brain imaging (e.g., Luauté, Halligan, Rode, Jacquin-Courtois, & Boisson, 2006, Chapman et al., 2010; Danckert, …) did by confirming lesion studies (e.g., Weiner, Hallett, & Funkenstein, 1983; Pisella et al. 2004, 2005; Hanajima et al. 2015). Innovative functional imaging paradigms and new investigations of functional connectivity should provide fresh insights into the mechanisms of prism adaptation and its expansion properties (e.g., Luauté et al., 2009; Crottaz-Herbette et al., 2017; Tissière et al., 2018).

One major challenge about prism adaptation has remained the extraordinary expansion of an apparently basic sensori-motor task to high level cognition (Jacquin-Courtois et al., 2013; Rossetti et al., 2015). Prism adaptation had long remained conceived of a sensori-motor task that could stimulate sensori-motor adaptation objectified by purely sensori-motor testing. Parameters used to describe prism adaptation have therefore been restricted to the error reduction curve (visual feedback available during prism exposure, i.e., closed-loop) and compensatory after-effects (tested without visual feedback after removal of prisms, i. open loop). The total shift (post minus pre measures of open-loop pointing to an untrained visual target) was defined as the global expression of adaptation: a measure of the visual-proprioceptive realignment (Welch, Choe, & Heinrich, 1974; Redding and Wallace book, Redding et al., 2005). Visual and proprioceptive shifts have been additionally used to disentangle between visual and proprioceptive contribution to the total realignment and the only window on prism adaptation has remained sensori-motor. Improvement of spatial cognition impairments seen in spatial neglect (Rode, Rossetti, Li, & Boisson, 1998; Rode et al. 2001; Rossetti et al., 1998) stood in sharp contrast with this long-standing sensori-motor tradition, and this contrast was further emphasised by the discovery that healthy subjects are also affected beyond the sensori-motor level (Colent et al., 2000). Even though it is a very general idea that cognition is grounded on sensorimotor interactions in both the field of developmental psychology (Piaget, 1962) and the more recent field of embodied cognition, prism adaptation offered the possibility to overtly alter cognition following a few minutes of a simple pointing task, opening a window onto this mysterious link between motor interactions with the environment and mental representations. A first wave of studies attempted to delineate in which domains and to what extent such sensorimotor to cognitive expansion of adaptation applies (e.g., Michel et al. 2001; 2003; Girardi et al., 2004; Striemer, Sablatnig, & Danckert, 2006; Fortis, Goedert, & Barrett, 2011). A second, ongoing wave of investigation has begun to explore the mechanisms of this expansion (Crottaz-Herbette et al., 2017, 2014; Martín-Arévalo et al., 2016; Tsujimoto et al. 2018) and much progress in our scientific conception of embodiment is expected from this endeavour.

At the clinical level three main important issues have to be addressed. First, we have to explore and define how to obtain the most intense, the most generalizable and the most durable effects (e.g., Hatada et al., 2006; O'Shea et al., 2014). Past studies have been trying to define the optimal exposure and optimal regime of prism adaptation (Fortis, Ronchi, Calzolari, Gallucci, & Vallar, 2013, 2018, 2010; Facchin, Bultitude, Mornati, Peverelli, & Daini, 2018; Frassinetti et al., 2002; Goedert, Zhang, & Barrett, 2015; Luauté et al., 2012; Rode et al., 2015; Vaes et al., 2018) and their efficacy in daily life activities (Champod, Frank, Taylor, & Eskes, 2018; Jacquin-Courtois et al., 2008; Mizuno et al., 2011; Watanabe & Amimoto, 2010). Accordingly, reviews have been emphasising the need for designing more systematic studies and increasing evidence levels (Barrett et al., 2012; Champod et al., 2018; Fasotti & van Kessel, 2013; Jacquin-Courtois et al., 2013; Luauté et al., 2006; Rode et al., 2006). However recent combinations of techniques have extensively renewed this question (e.g., Guinet et al., 2013; Làdavas et al., 2015; Luauté et al., 2018; O'Shea et al., 2017) and much development is expected in the near future on this point. Second, it is of prime importance to be able to predict whether an individual patient is likely to benefit from prism adaptation, and whether this method should be used alone or in combination with other techniques. Third, further exploration are likely to uncover other domains of application of prism adaptation. So far the available evidence that it can improve spatial neglect (Rossetti et al., 1998), postural control in left hemiparesis (Tilikete et al., 2001) and neglect (Nijboer et al. 2014), spatial dysgraphia (Rode et al., 2006a), constructional deficits (Rode et al., 2006b) or complex regional pain syndrome (Christophe 2016; Sumitani et al., 2007) does not allow to provide a clear and integrated framework to define its application fields. Last, and most perspective gaining is the idea that therapeutical interventions such as prism adaptation may backward shed light on the pathophysiology of the relevant conditions. Beneficial effects of prism adaptation and identification of affected clinical and psychophysical parameters have begun to stimulate new conceptions of the neurophysiological and maladaptive mechanisms leading to impairments (e.g., Milner & McIntosh, 2005; Newport & Schenk, 2012; Rode, Fourtassi, Pagliari, Pisella, & Rossetti, 2017; Rossetti et al., 2015; Striemer & Danckert, 2010).

This special issue of Cortex is devoted at paving the ground for the future explorations of the relationship between sensori-motor adaptation and spatial cognition's physiology, patho-physiology and therapeutico-physiology. This first virtual special issue of Cortex will be gathering the most advanced theoretical and methodological, basic empirical and clinical contributions ranging from case reports to large group studies and from refined behavioural to neural approaches, with the aim of contributing to a field that has begun to considerably renew our approaches and understanding of the dynamical interactions between action and cognition.



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