

ORIGINAL ARTICLE

The effect of different reaching interval on the course of prism adaptation

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Abstract

Quick, accurate and precise reaching to a visual target is considered to be acquired by visuomotor learning or adaptation, during which both visual and proprioceptive feedback is required. The course of adaptation and its neural basis have been investigated using a robotic arm that can change force while reaching, and by using a prism that can shift the visual field horizontally to left/right. The former process is known as ‘force-field adaptation’, where the main types of feedback are visual and proprioceptive feedback, and the latter is known as ‘prism adaptation’, where visual feedback is considered to be the main feedback. Previous force-field adaptation studies have shown that the interval between each reaching should be around 1 sec to allow full and efficient use of feedback information, but the optimum interval has not yet been examined in prism adaptation. To examine whether or not the difference in reaching interval is also affected efficiency in prism adaptation, we developed a different setup from that used in the ordinary experiments, which enabled shorter (< 1 sec) interval of reaching in prism adaptation. Although both > 1 sec and < 1 sec interval of reaching showed clear prism adaptation, significantly faster adaptation was observed when there was > 1 sec interval of reaching. This result is consistent with those in force-field adaptation studies. Further investigation using an approximately 1 sec interval of reaching in prism adaptation would be comparable with that in force-field adaptation.

Key words: prism adaptation, reaching, feedback

INTRODUCTION

We can usually reach out and place our fingertips on a target in the visual field quickly and accurately (Flash, 1985; Uhlariuk, 1973). Such accuracy in reaching a target is thought to be acquired through learning of visuomotor transformation, in which learning information of the visual location of a target (visual stimuli) is transformed into appropriate motor information. Many studies on this learning process have been conducted using the conventional wedge-shaped prism (hereafter: ‘prism’) or, more recently, with the manipulandum, a device used to examine the adaptation and learning process of subjects’ reaching movements in a virtual dynamic environment generated by manipulators (Shadmehr, 2005). The former process is specifically referred to as ‘prism adaptation’ whereas the latter is referred to as ‘force-field adaptation’.

The prism placed in front of the eyes shifts the field of view either vertically or horizontally, or to form a vertical or horizontal mirror image, thereby changing and displacing the subject’s reaching point. For ex-

ample, if a subject looked through a prism that shifts the field of view to the right and attempted to quickly reach a target in the field of view, the finger would initially reach a position that would be displaced to the right of the target (Redding, 2005). However, this displacement would gradually decrease with each reaching attempt (Kitazawa, 1997), and after about 15 trials (Redding, 1993; Rock, 1966), it would become almost as accurate as it was when the prism was not used. Learning visuomotor transformation, as has been shown by this adaptation to seeing through the prism, is considered to be a type of procedural or motor learning, and is thought to be an example of the acquisition process of procedural memory (Redding, 1993; Rock, 1966) and nondeclarative memory (Harris, 1965; Shadmehr, 2005).

In general, feedback of results after motor output is important to establish motor learning, including prism adaptation (Harris, 1965; Shadmehr, 2005). ‘Motor error’ is the magnitude of the deviation between the motor commands generated in the brain to reach a

target and the actual reaching point. In prism adaptation, the motor commands for reaching are thought to be repeatedly corrected based on mostly visual motor error feedback (Harris, 1965; Shadmehr, 2005). To realize this, there should be appropriate association between the motor error obtained in the previous reaching and the motor command for the next reaching (Ikegami, 2012), so some time would be needed between the motor error and the next reaching. In studies using a manipulandum, motor error is considered to be obtained via vision as well as proprioception from muscles (Shadmehr, 2005), and at least 1 sec is required for efficient motor error feedback before the next reaching (Francis, 2005). However, in the prism adaptation, in which vision is thought to be the main source of feedback, it has not yet been confirmed whether a reaching interval of more than or less than 1 sec influences the adaptation.

In the present study, we therefore examine the prism adaptation efficiency of reaching interval of < 1 sec compared with >1 sec, and compare change in reaching end point (displacement) during the course of prism adaptation.

METHODS

Subjects

Fifteen healthy students of Gunma Paz University participated as subjects (mean age: 21.5 ± 0.5). All were right-handed according to the Edinburgh Handedness Inventory and had normal or corrected-to-normal vision. The experimental procedures were approved by the Gunma Paz University Institu-

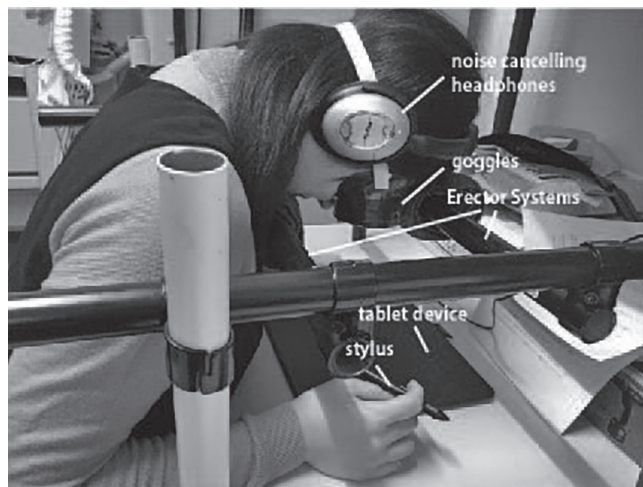


Figure 1. Subjects' posture and apparatus during experiments. Subjects wore goggles and noise-cancelling headphones. They were seated on height-adjusted chair looking down with their forehead and chin placed on the erector system so that the distance between the eyes and the tablet device were always located 19 cm below.

tional Ethics Review Committee (PAZ21-24) and were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All subjects gave their informed consent prior to being included in the study.

Task procedure

Subjects' posture and apparatus

Subjects were seated on a height-adjusted chair and looked down (Figure 1) with their forehead and chin placed and fixed on a specially-constructed Erector System (CREFORM, Yazaki Kako Corporation) so that a tablet device (TH69, Wacom) was fixed at approximately 19 cm away from their eyes. A white circular target (2° visual angle diameter) was set at the center of the tablet device. Subjects wore noise cancelling headphones (Quiet Comfort 15, BOSE) to reduce environmental noises. During the experiment, a metronome beep (1 kHz) and white noise sound was played into the headphones. The volume of those sounds was adjusted by the subjects before the experiment began. Subjects also wore goggles with restricted vertical visual field (Figure 2a) so that they could only see the pen tip when it was held close to the target. A prism (LP-40-0.3, NTKJ Co. Ltd.) that can refract visual field horizontally by 40° was mounted on the goggles during the activity described below.

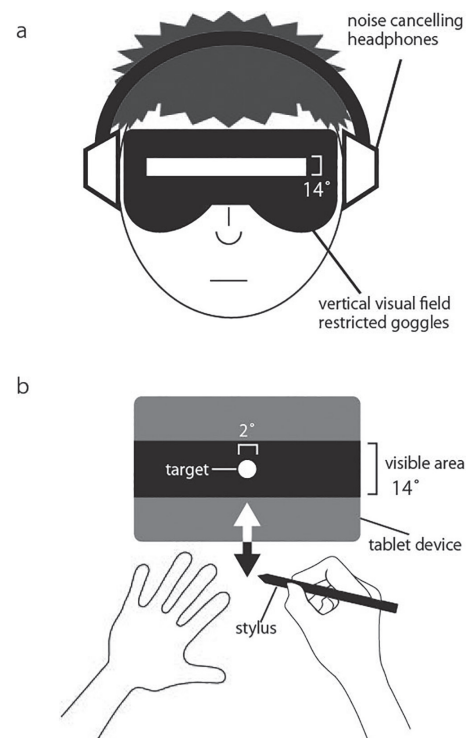


Figure 2. Visual field restricted goggles (a) and reaching task (b). Subjects performed the reaching task while their visual field was restricted, as shown in (a). Subjects hold the stylus with either hand and reach the target on the tablet device and repeatedly draw back immediately after the reaching (b).

Reaching task

In the present study, participants aimed to reach the target repeatedly to the rhythm of the metronome beep as accurately as possible and as fast as possible with the stylus holding in either hand with the prism mounted or unmounted (control) on the goggles (Figure 2b). Subjects were told to draw back the stylus out of the visual field immediately after the reaching so the total time of each reaching would be the same, despite differing reaching interval. It was also allowed some control over the processing time of visual feedback information. A trial was composed of the participant starting reaching and then drawing back from reaching.

The task was performed in both control condition and prism condition. The control condition was introduced to ensure that subjects could reach the target accurately without the prism being mounted on the goggles, and was comprised of 50 consecutive repetitions. After assessment of the control condition, the participants performed 45 consecutive repetitions in the prism condition. This was used to examine the course of prism adaptation. The prism was mounted on the goggles and the direction of horizontal refraction (left/right shift) was fixed within the condition. Then, another series of repetitions in the control condition was then followed by more in the prism condition. The sequence of conditions composed one experimental set (Figure 3, control condition, then prism condition, then control condition again). During an experimental set, participants were required to reach the target to the beep rhythm of either 0.5 or 1.5 Hz (2.00 and 0.67 sec, respectively) without changing the hand holding the tablet pen. The order of the combinations of the direction of prism shift (left/right), reaching interval (2.00/0.67 sec), responding hand (left/right) were randomized and counter-balanced across subjects and each participant did eight sets

of experiment per day. The position of the target was adjusted to the center of visual field before each condition of experiment was started.

The reached positions pointed by stylus were collected as X-Y coordinate data with time stamps through the USER FORM function of Microsoft Excel 2010 (Microsoft Corporation) on a Windows 10 PC (CPU: Core i7 4770K).

Statistical analysis

Generally, X-Y coordinate data, especially X-axis value, obtained during prism condition are analyzed in prism adaptation studies and the amount of prism shift may differ from the magnitude of displacement (Rock, 1966). In the present study, the average value of the X-axis values of the 10 trials in the first control condition just before the prism condition was therefore standardized to be 0% and the maximum displaced value of the x-axis value under the prism condition was standardized to be 100% for each set of experiment.

Four-way repeated measures analysis of variance (RM-ANOVA) was then performed using SPSS 25.0J (SPSS Inc., Chicago, IL, USA) as statistical analysis, and the significance level was set at 0.05. The factors were direction of prism shift (left and right, factor of PRISM), hand to reach (left and right, factor of HAND), reaching interval (0.5 Hz and 1.5 Hz, factor of INTERVAL), and trials of prism adaptation (1-20 trials, factor of TRIAL).

RESULTS

Four-way RM-ANOVA revealed a significant difference in main effect of TRIAL ($F(19, 266) = 98.998, p < 0.05$, Figure 4a). In the first and second trials of the prism condition, the horizontal displacement from the target was significantly larger than that in the follow-

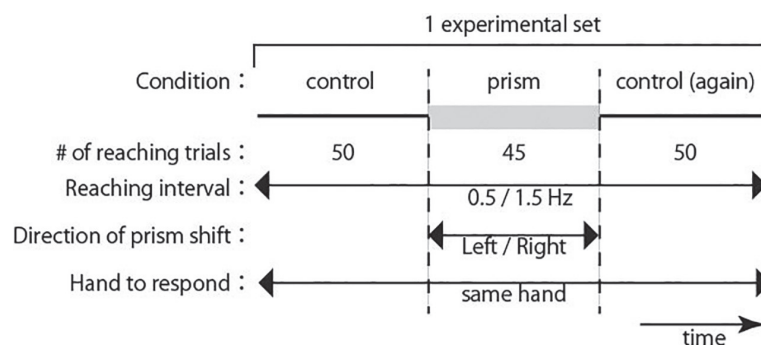


Figure 3. Design of one set of the reaching task

In the reaching task, subjects performed alternately under control and prism conditions. Within each condition, the reaching interval, direction of prism shift and hand to respond were fixed.

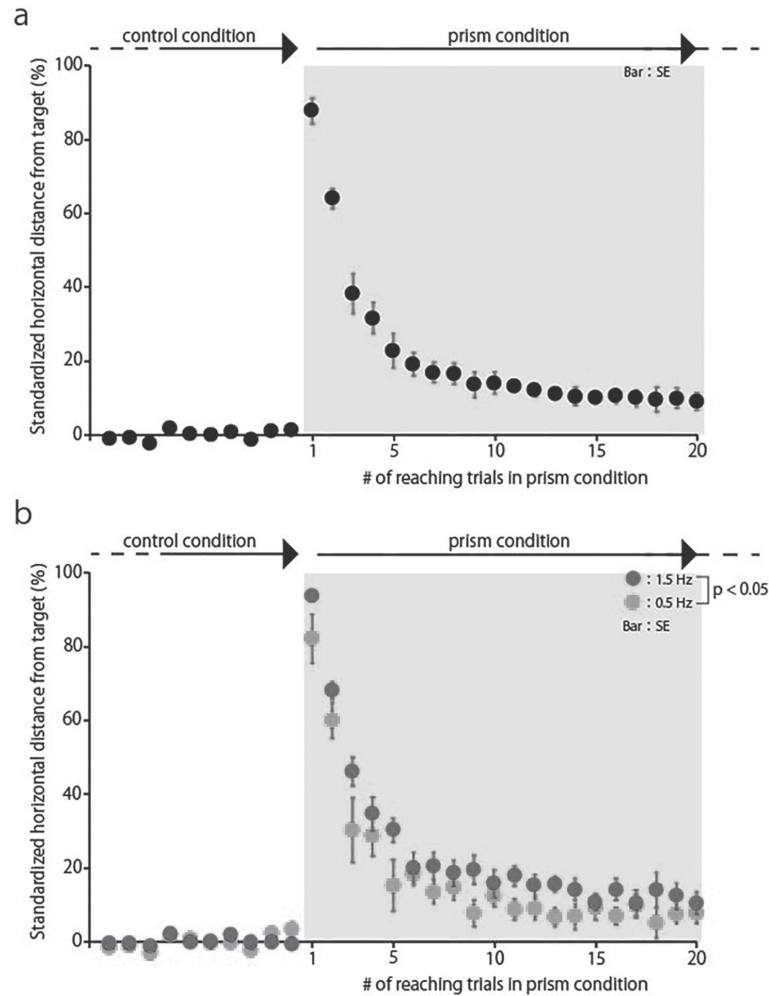


Figure 4. Overall average of % displacement of control condition and prism condition (a) and those with different reaching interval (b). The last ten trials of control condition 1 and first 20 trials of prism condition were shown. Four-way RM ANOVA revealed significant main effect of TRIAL (a) and INTERVAL (b).

ing trials ($p < 0.05$). In the third and fourth trials, the displacement was significantly larger than that in the following trials ($p < 0.05$) except that in the fourth and fifth trials, respectively ($p > 0.05$). After the fifth trial, the displacement was not significantly larger than that in the following trials ($p > 0.05$).

Four-way RM-ANOVA also revealed a significant difference in main effect of INTERVAL ($F(1, 14) = 4.906$, $p < 0.05$, Figure 4b). showing that the displacement from the target was significantly smaller if the reaching interval was 0.5 Hz compared with if that was 1.5 Hz, even in the same trial experience. However, there was no significant difference in main effect of PRISM and HAND ($p > 0.05$).

DISCUSSION

The present study examined prism adaptation efficiency by changing subjects' reaching interval of 0.5

Hz and 1.5 Hz. Similar to the previous studies that used manipulandum, the distance between the target and the reaching endpoint decreased with fewer trials if the reaching interval was > 1 sec, suggesting that adaptation became more efficient. This result was observed regardless of the direction of prism shift and hand used.

Setups in previous studies

Although the current experiment was not especially complex, no previous studies required subjects to reach the target repeatedly with < 1 sec interval. We suggest two main reasons for this.

First, the small scale of the setup could be a reason. In the present study, the experimental setup was devised to realize reaching the target with < 1 sec interval. Subjects faced down and repeatedly reach the target located 19 cm in front of their eyes by repeatedly moving the stylus tip between visible

and invisible areas (distance: < 15 cm, Figure 2b). On the other hand, in a previous study (Kitazawa, 1995), the distance from the front-facing subject to the front monitor was 40 cm, the reaching distance was about 50 cm, and a ball or other object was thrown instead of reaching. Elsewhere, (Fernandez-Ruiz, 1999), a target was drawn on a large piece of paper 2 m away from the subject. In other words, these setups were not designed for short interval reaching or throwing to the target.

The robustness of the setup is another difference from previous studies. Most previous prism adaptation studies used the touch panels. When frequent reaching was performed in such studies, the distance would be longer and the speed of reaching itself would be faster, which may damage the fragile touch panels. On the other hand, the manipulandum is a device that is designed for a strong force to be applied, and its mechanism can withstand the impact caused by frequent and rapid reaching (Ikegami, 2012). In the current study, a more robust tablet device and shorter reaching distance was adopted, taking into account the impact caused by the frequent reaching.

Feedback interval and motor learning

Motor learning is considered to be established by two main types of feedback: intrinsic feedback and extrinsic feedback. Intrinsic feedback is provided via visual and proprioceptive receptors, while extrinsic feedback is provided via language, measuring devices and rewards (Wulf, 1993; Wulf, 1996). Prism adaptation is considered to be established by intrinsic (primarily visual) feedback (Rock, 1966; Shadmehr, 2005). Generally, whether the feedback is intrinsic or not, too frequent feedback leads to poorer results in motor learning (Bock, 2005; Francis, 2005; Nicholson, 1991; Uno, 1989; Weeks, 1998; Winstein, 1990; Wulf, 1994; Wulf, 1989; Wulf, 2002). In the motor learning studies other than prism adaptation, feedback is considered to be less effective if the motor response interval was < 1 sec (Bock, 2005; Francis, 2005). These results are considered to be due to the learning requiring physiological processing and plasticity in the brain, so too frequent and/or too short interval of motor response causes immature plasticity and slower learning (Ikegami, 2012). However, less learning efficiency has also been shown if the interval was too long (15-20 sec) (Weeks, 1998; Wulf, 1993). This is considered to be because feedback information corrupts over time, so that taking too much time makes inability to modify the motor command to appropriately and effectively generate the next correct-

ed motor response (Huang, 2007).

Unlike adaptation using manipulandum, which proceeds based on feedback from both visual and proprioceptive information, prism adaptation is generally considered to be proceeded mainly based on feedback from visual information only, because the goggles restrict the visible area (Figure 2b) and the target in prism adaptation is presented at a random position each time so that the proprioceptive feedback can be cancelled. The amount of visual feedback can influence the efficacy of prism adaptation. For example, in a previous study, if an upper limb was visible at the end of reaching, the adaptation was facilitated compared to that only the fingertip at the reaching endpoint was visible at the end of reaching (Redding, 1988). Visual feedback is thought to begin to be input into the brain during the reaching, while with restricted field of vision, this input begins only at the end of the reaching. Furthermore, if participants could watch the entire trajectory of the reaching from the start to the end, the mounting prism does not cause displacement of the reaching endpoint (Redding, 1996; Redding, 1988), and similar results would be produced by very slow reaching speed (Redding, 2005). Mounting of the prism reportedly produces little or no endpoint reaching displacement if the refractive power of the prism is so weak that the subject does not notice it, or if the refractive power of prism increases gradually (Dewar, 1971; Howard, 1974; Jakobson, 1989; Templeton, 1974; Uhlarik, 1973).

The present study conducted prism adaptation experiments with reaching intervals of > 1 sec and < 1 sec. The results at > 1sec suggested that there was sufficient time between each reaching for plasticity to be established in brain, whereas results at < 1sec suggested insufficient time for plasticity. As also shown in previous studies (Redding, 1993; Rossetti, 1993), our results showed gradual decrease of displacement between the reaching end point and the target position, possibly due to the limitation of the subjects' field of view by wearing goggles that enabled them to see only the stylus tip that reached the target. However, our results seemed to show slightly faster adaptation (approx. 5 trials, Fig. 4a) compared with that in previous studies (approx. 15 trials). This may be because the target in our study was presented in a fixed position rather than freely positioned as seen in the previous studies. Although subjects moved their fingers and stylus out of the visual field immediately after reaching, adaptation might also be progressed through proprioception. This situation is similar to the adaptation using manipulandum and the

reason why the present results were similar to those in the previous studies using manipulandum.

Prism adaptation by rhythmic reaching

Everyday behaviors are consisted of two distinct movements: discrete and rhythmic. Discrete movement is represented by reaching the fingers to a target, and rhythmic movement is clapping and walking. To clarify the neural processes required to generate these movements, previous studies have extensively examined three alternative hypotheses. The first hypothesis is that discrete movements are fundamental, whereas rhythmic movements are mere concatenations of discrete movements (Feldman, 1980; Shadmehr, 2005). A second hypothesis is that rhythmic movements are fundamental, whereas discrete movements are truncated rhythmic movement (Mottet, 1999; Schöner, 1990). The third hypothesis is that rhythmic and discrete movements are two different classes of movements (Buchanan, 2003; Ikegami, 2010; Schaal, 2004; Sternad, 2000). These hypotheses have been examined from behavioral (Buchanan, 2003), theoretical (Huys, 2008) and neuronal (Schaal, 2004) perspectives, and the current consensus is that the first hypothesis is ruled out. Although it is still unknown which of the remaining hypotheses is the most accurate, according to the neuroscientific fact that there is close relationship between motor control and motor learning, some studies have suggested the greater likelihood of the third hypothesis. The transfer of memory acquired through motor learning of rhythmic and discrete movements using manipulandum has been examined (Ikegami, 2010). What subjects learned from the motor learning of rhythmic movements reportedly did not transfer to the execution of discrete movements, so it was concluded that control processes of rhythmic and discrete movements are different in brain (Ikegami, 2010). Further, fMRI studies have shown that despite the same wrist movements, a wider range of brain regions are involved during the expression of discrete movements than during rhythmic movements, supporting the idea that rhythmic and discrete movements are two different classes of movements (Schaal, 2004). The present study examined the prism adaptation efficiency by adopting different frequency of reaching. The reaching of longer interval in the present study could be called discrete reaching, whereas that of shorter interval could be rhythmic reaching. The present study could therefore also be said to have examined the adaptation efficiency between discrete and rhythmic reaching. However, unlike a previous study (Ikegami,

2010), the present study did not intend to clarify the processing of discrete and rhythmic reaching, so further study is required.

Conclusion

The present study was the first to examine the prism adaptation efficiency by comparing reaching at > 1 sec and < 1 sec intervals. Faster adaptation by reaching at > 1 sec was shown, and was comparable to previous studies using manipulandum, suggesting that the studies conducted using expensive manipulandum setups can be replaced. However, the reaching itself might be limited to shorter distances compared with those using manipulandum, which can be used to examine reaching with arms fully extended. The neural basis might therefore be different between these types of reaching, even if the interval was the same. Further studies are required, and will additionally aim to clarify the threshold of prism adaptation efficiency.

Author contributions

In this study, SA performed all experiments and analyses and drafted this paper. TH designed this study, procured the research funding and equipment, and completed this paper by adding to and revising the draft prepared by SA.

REFERENCES

- Bock O, Thomas M, et al. The effect of rest breaks on human sensorimotor adaptation. *Exp Brain Res* 163, 258-260, 2005
- Buchanan J, Park J, et al. Discrete and cyclical units of action in a mixed target pair aiming task. *Exp Brain Res* 150, 473-489, 2003
- Dewar RE Adaptation to displaced vision: Variations on the "prismatic-shaping" technique. *Perception & Psychophysics* 9, 155-157, 1971
- Feldman AG Superposition of motor programs—I. Rhythmic forearm movements in man. *Neuroscience* 5, 81-90, 1980
- Fernandez-Ruiz J, Diaz R Prism adaptation and aftereffect: specifying the properties of a procedural memory system. *Learn Mem* 6, 47-53, 1999
- Flash T, Hogan N The coordination of arm movements: an experimentally confirmed mathematical model. *J Neurosci* 5, 1688-1703, 1985
- Francis JT Influence of the inter-reach-interval on motor learning. *Exp Brain Res* 167, 128-131, 2005
- Harris CS Perceptual adaptation to inverted, reversed, and displaced vision. *Psychol Rev* 72, 419-444, 1965
- Howard IP, Anstis T, et al. The relative lability of mobile and stationary components in a visual-motor adaptation task. *Q J Exp Psychol* 26, 293-300, 1974
- Huang VS, Shadmehr R Evolution of motor memory during the seconds after observation of motor error. *J Neurophysiol* 97, 3976-3985, 2007
- Huys R, Studenka BE, et al. Distinct timing mechanisms produce discrete and continuous movements. *PLoS Comput Biol* 4, e1000061, 2008
- Ikegami T, Hirashima M, et al. Intermittent visual feedback can

- boost motor learning of rhythmic movements: evidence for error feedback beyond cycles. *J Neurosci* 32, 653-657, 2012
- Ikegami T, Hirashima M, et al. Asymmetric transfer of visuomotor learning between discrete and rhythmic movements. *J Neurosci* 30, 4515-4521, 2010
- Jakobson LS, Goodale MA Trajectories of reaches to prismatically-displaced targets: evidence for "automatic" visuomotor recalibration. *Exp Brain Res* 78, 575-587, 1989
- Kitazawa S, Kimura T, et al. Prism adaptation of reaching movements: specificity for the velocity of reaching. *J Neurosci* 17, 1481-1492, 1997
- Kitazawa S, Kohno T, et al. Effects of delayed visual information on the rate and amount of prism adaptation in the human. *J Neurosci* 15, 7644-7652, 1995
- Mottet D, and Bootsma RJ. The dynamics of goal-directed rhythmic aiming. *Biol Cybern* 80, 235-245, 1999
- Nicholson DE, Schmidt RA Scheduling information feedback to enhance training effectiveness. In: *Proceedings of the Human Factors Society 35th Annual Meeting*. Santa Monica, CA: Human Factors Society, 1400-1403, 1991
- Redding GM, Rossetti Y, et al. Applications of prism adaptation: a tutorial in theory and method. *Neurosci Biobehav Rev* 29, 431-444, 2005
- Redding GM, Wallace B Adaptive coordination and alignment of eye and hand. *J Mot Behav* 25, 75-88, 1993
- Redding GM, Wallace B Adaptive spatial alignment and strategic perceptual-motor control. *J Exp Psychol Hum Percept Perform* 22, 379-394, 1996
- Redding GM, Wallace B Components of prism adaptation in terminal and concurrent exposure: organization of the eye-hand coordination loop. *Percept Psychophys* 44, 59-68, 1988
- Rock I, Goldberg J, et al. Immediate correction and adaptation based on viewing a prismatically displaced scene. *Percept Psychophys* 1, 351-354, 1966
- Rossetti Y, Koga K, et al. Prismatic displacement of vision induces transient changes in the timing of eye-hand coordination. *Percept Psychophys* 54, 355-364, 1993
- Schaal S, Sternad D, et al. Rhythmic arm movement is not discrete. *Nat Neurosci* 7, 1136-1143, 2004
- Schöner G A dynamic theory of coordination of discrete movement. *Biol Cybern* 63, 257-270, 1990
- Shadmehr R, Wise S The computational neurobiology of reaching and pointing: a foundation of motor learning. Cambridge, MA: MIT, 2005
- Sternad D, Dean W, et al. Interaction of rhythmic and discrete pattern generators in single-joint movements. *Human Movement Science* 19, 627-664, 2000
- Templeton WB, Howard IP, et al. Additivity of components of prismatic adaptation. *Perception & Psychophysics* 15, 249-257, 1974
- Uhlirik JJ Role of cognitive factors on adaptation to prismatic displacement. *J Exp Psychol* 98, 223-232, 1973
- Uno Y, Kawato M, et al. Formation and control of optimal trajectory in human multijoint arm movement. Minimum torque-change model. *Biol Cybern* 61, 89-101, 1989
- Weeks DL, Kordus RN Relative frequency of knowledge of performance and motor skill learning. *Res Q Exerc Sport* 69, 224-230, 1998
- Winstein CJ, Schmidt, RA Reduced Frequency of knowledge of Results Enhances Motor Skill Learning. *Journal of Experimental Psychology* 16, 677-691, 1990
- Wulf G, Lee TD, et al. Reducing knowledge of results about relative versus absolute timing: Differential effects on learning. *J Mot Behav* 26, 362-369, 1994
- Wulf G, Schmidt RA The learning of generalized motor programs: Reducing the relative frequency of knowledge of results enhances memory. *J Exp Psychol Learn Mem Cogn* 15, 748-757, 1989
- Wulf G, Schmidt RA, et al. Reduced feedback frequency enhances generalized motor program learning but not parameterization learning. *J Exp Psychol Learn Mem Cogn* 19, 1134-1150, 1993
- Wulf G, Shea CH Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychon Bull Rev* 9, 185-211, 2002
- Wulf G, Shea JB, et al. Type of KR and KR frequency effects on motor learning. *Journal of Human Movement Studies* 30, 1-18, 1996