

Secondary tasks impair adaptation to step- and gradual-visual displacements

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Abstract Motor adaptation is impaired by the performance of a secondary task which divides cognitive resources. Additionally, we previously reported slowed adaptation when participants were required to switch from one visual displacement adaptation task to another. Here, we examined whether a dividing secondary task had a similar effect on adaptation as switching between opposing visual displacements. The resource-dividing task involved simultaneously adapting to a step-visual displacement whilst vocally shadowing an auditory stimulus. The switching task required participants to adapt to opposing visual displacements in an alternating manner with the left and right hands. We found that both manipulations had a detrimental effect on adaptation rate. We then integrated these tasks and found the combination caused a greater decrease in adaptation rate than either manipulation in isolation. A second set of experiments showed that adaptation to a gradually imposed visual displacement was influenced in a similar manner to step adaptation. In summary, step adaptation slows the learning rate of gradual adaptation to a large degree, whereas gradual adaptation only slightly slows the learning rate of step adaptation. Therefore, although gradual adaptation involves minimal

awareness it can still be disrupted with a cognitively demanding secondary task. We propose that awareness and cognitive resource can be regarded as qualitatively different, but that awareness may be a marker of the amount of resource required. For example, large errors are both noticed and require substantial cognitive resource. However, a lack of awareness does not mean an adaptation task will be resistant to interference from a resource-consuming secondary task.

Keywords Attention · Cognitive · Interference · Learning · Motor adaptation

Introduction

Within motor adaptation a distinction is often made between explicit and implicit levels of information processing (Hwang et al. 2006; Malfait and Ostry 2004; Vangheluwe et al. 2005). Specifically, during adaptation to gradual changes, limited visual and kinesthetic input arise from the perturbation; these sensory inputs occur beyond awareness (Ingram et al. 2000; Klassen et al. 2005; Malfait and Ostry 2004) and thus the resulting adaptation is regarded as implicit. In contrast, adaptation to abrupt changes in the environment such as a sudden load or prismatic displacement relies substantially on the use of high-level explicit (cognitive) information which is independent of the implicit, predictive changes in muscle activity (Criscimagna-Hemmingner et al. 2003; Malfait and Ostry 2004). An assumption underlying this separation is that explicit tasks have greater engagement of attention and cognitive resources than implicit tasks. However, Mazzoni and Krakauer (2006) showed that an explicit adaptation strategy does not interfere with the underlying adaptation

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to a step-visual displacement. Though this suggests that step and gradual adaptation may both involve implicit processes, there is still the distinction that step adaptation involves awareness: it has an additional explicit component that requires cognitive resources.

Secondary tasks have often been used to assess the cognitive requirements of an adaptive task. Eversheim and Bock (2001) showed that four separate secondary tasks interfered with adaptation to a step-visual displacement. Importantly, the time-course of adaptation was different for each task, suggesting interference was sensitive to the resource requirements of the secondary task. In addition Taylor and Thoroughman (2007) showed a resource-dividing secondary task which required participants to concurrently perform an auditory frequency discrimination task resulted in impaired adaptation to an abrupt dynamic force-field. We have previously reported a similar result with a switching task in which the two hands adapted to opposing step-visual displacements during alternating unimanual movements (Galea and Miall 2006). Despite the apparent similarity of the two results, it is possible that the interference observed from task switching in our alternating task is fundamentally different from the resource-dividing task effects reported by Taylor and Thoroughman (2007) and Eversheim and Bock (2001).

As previously mentioned gradual adaptation has been shown to occur without awareness, supporting the notion that it is implicit (Ingram et al. 2000; Klassen et al. 2005; Malfait and Ostry 2004). However, it is not known whether substantial cognitive resources are still required for the task. Hence, the aim of this study was to assess how dividing and switching secondary tasks influenced the rate of adaptation during a visuomotor displacement that either involved a large (step) or small (gradual) amount of visual error.

There are two possibilities; first, the secondary tasks may only influence adaptation when the errors are large. This would indicate that cognitive demands and awareness are qualitatively similar. Secondly, the secondary tasks influence adaptation when the errors are either large or small. This would suggest awareness and cognitive demands are qualitatively different. In Experiment 1, the effects of a dividing and switching task on the learning of a single large visuomotor displacement are investigated. In Experiment 2, the effects of a dividing and switching task on the learning of a gradually increasing visuomotor displacement are investigated.

Experiment 1

Experiment 1 was conducted to assess whether a secondary cognitive task (resource dividing) had a different effect on

unimanual adaptation than alternating adaptation to a visual displacement in the opposite limb (resource or task switching). Task switching could require switching between either a learning environment (i.e., learning a single-step clockwise rotation with the right hand and a gradual counterclockwise rotation with the left hand) or switching between two more similar (but independent) learning environments (i.e., learning different single-step rotations with the right and left hands). In addition, the combination of a switching (opposite limb adaptation) and dividing (secondary cognitive task) task on adaptation rate was assessed. This provided a baseline as to the amount of interference observed during adaptation which could then be used during Experiment 2 to assess whether similar interference occurred during gradual adaptation.

Method

Participants

Thirty-six right-handed participants (25 female, age = 20 ± 2 years, mean \pm SD) participated in the experiment. Handedness (mean = 75, decile R.4) was assessed using the ten-item version of the Edinburgh inventory (Oldfield 1971). All participants signed a consent form and were either given course credit or financial compensation for their participation. This study was approved by the school ethics committee and was in accordance with ethical standards of the 1964 Declaration of Helsinki.

Materials

Each participant sat at a table facing a computer screen approximately 1 m in front of them. A marker from an Optotrak (NDI, Ontario, Canada) position tracking system was attached to the index finger of each hand. Goggles were worn with horizontal blinders that ensured the participant could see the screen, but their arms were not visible.

The experimental setup is shown in Fig. 1. The presentation on the computer screen consisted of two white solid discs (20 mm in diameter) indicating in real time the 2D position of the participant's index fingers on the tabletop, and four yellow circles (35 mm in diameter). The two yellow circles at the bottom of the screen were the starting positions (140 mm horizontally separate), while the two at the top represented the targets. The targets were 120 mm vertically parallel to the starting positions. An angular displacement could be applied to either disc representing their finger positions. This rotation of visual feedback was calculated relative to the starting circle of each hand, in a clockwise (CW) or counter clockwise (CCW) direction.

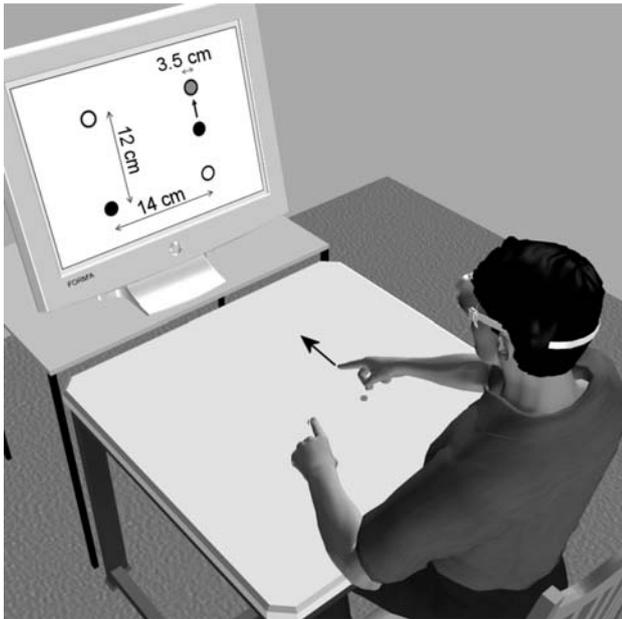


Fig. 1 The experimental setup. A movement away from the participant corresponded to a vertical movement on the screen. Participants wore goggles ensuring their arms were not visible. The two *solid black circles* indicate index finger position. The two bottom markers represent the starting positions and the two top markers are the targets (yellow in the actual experiment). When the target changed color (*grey circle*, green in the actual experiment) it was the signal for the participant to make a movement towards it with the appropriate limb

Procedure

The participants were asked to place their index fingers on two markers which indicated the starting positions on the table. These were slightly raised and textured, providing tactile cues of the starting positions. The participants were informed that their index fingertips were the only part of their body which should be in contact with the table. They were told that the experiment involved making forward-pointing movements on the table in front of them, which corresponded to upward vertical movements of the cursors on the screen.

The participants were informed that when a target circle turned green they should make a pointing movement towards that target with the corresponding finger while ensuring their other finger did not leave the starting position. The participants had online feedback (white discs) but were instructed to make a single straight movement towards the target and once their finger had touched the table not to make any additional corrections. Movement time was constrained to 300–600 ms; if this was not achieved, the disc representing their finger changed color to red if they were too slow and blue if they were too fast.

The starting circles then turned green indicating to the participant that they should move back. When both fingers were again placed within the starting positions a ‘dwell’

period began and the participants had to wait for the next target to turn green. The ‘dwell’ time was varied from 2 to 8 s (mean = 4 s) so that participants could not anticipate when to move and were unable to engage in a rhythmic movement. The instructions to the participants placed an emphasis on producing fast and straight movements to the target.

There were six groups ($n = 6$) with three test phases (Table 1). For all groups the pre-adaptation and post-adaptation phases consisted of 20 trials for each active limb. For all groups only one hand was active at any one time. For unimanual groups only the right hand was active. For the alternating groups each hand moved towards a target in an alternating fashion.

For two groups the pre-adaptation and adaptation phases consisted of unimanual right-hand pointing movements performed independently (Rs–) or with an additional secondary cognitive task (Rs+). For the four other groups, the pre-adaptation and adaptation phases involved alternating left- and right-hand pointing movements performed either independently (RsLs–, RsLg–) or with an additional secondary cognitive task (RsLs+, RsLg+). The pre-adaptation phase was always under veridical conditions. The adaptation phase involved a 30° clockwise (CW) step (s) visual displacement for the right hand. For the RsLs– and RsLs+ groups the left hand was exposed to a 30° counterclockwise (CCW) step displacement. In contrast, within the RsLg– and RsLg+ groups the left hand was exposed to a CCW gradual (g) displacement, which began at 0° and incremented by 0.25° per trial. During the post-adaptation phase all groups moved towards targets under veridical conditions, with no secondary cognitive task.

These six groups experienced conditions with different combinations of attentional components. The Rs– group experienced a single-adaptation task and is used as the adaptation baseline. The Rs+, RsLs– and RsLg– groups each experienced two tasks: the Rs+ group experienced unimanual adaptation and a secondary shadowing task while the RsLs– and RsLg– groups experienced opposing adaptation in the left and right hands. Comparing these groups will identify whether there are different effects on the adaptation rate when the task is constantly divided or repeatedly switched. The RsLs+ and RsLg+ groups experienced three tasks as the adaptation phase involved opposing adaptation in the left and right hands along with a secondary shadowing task. These groups will show the effects of simultaneously switching and dividing the task.

The secondary vocal shadowing task involved the participants listening to an audio story through headphones and repeating it back to the experimenter word for word. Each participant was told to concentrate on this task and to try and not miss any words. The secondary task ensured the participant was constantly engaged throughout the

Table 1 Experiment 1 groups ($n = 6$)

Group ($n = 6$)	Pre-adaptation (20 trials for each active limb)	Adaptation (60 trials for each active limb)	Post-adaptation (20 trials for each active limb)
Rs–	Null	R = CW	Null
Rs+	Null	R = CW (+secondary task)	Null
RsLs–	Null	R = CW L = CCW	Null
RsLs+	Null	R = CW L = CCW (+secondary task)	Null
RsLg–	Null	R = CW L = gradual CCW	Null
RsLg+	Null	R = CW L = gradual CCW (+secondary task)	Null

For two groups the participants performed unimanual right-hand pointing movements independently (Rs–) or with an additional secondary cognitive task (Rs+). For four other groups the participants performed alternating left and right-hand pointing movements independently (RsLs–, RsLg–) or with an additional secondary cognitive task (RsLs+, RsLg+). Pre-adaptation consisted of movements under null conditions. The adaptation phase involved a 30° CW step-visual displacement for the right hand and, for the alternating groups, either a 30° step CCW displacement (RsLs–, RsLs+) or 30° gradual CCW displacement (RsLg–, RsLg+) for the left hand. During the post-adaptation phase all groups moved towards targets under null conditions, with no secondary cognitive task

experiment, ensuring that attention was divided during the entire performance of the adaptation tasks. Taylor and Thoroughman (2007) have previously shown that an audio discrimination task can disrupt motor adaptation.

Analysis

The 2D position of each index finger in the horizontal plane was continuously recorded at a rate of 60 Hz via the Optotrak system. Using Matlab (Mathworks, Matick, MA) all kinematic data were filtered at 10 Hz with a low-pass Butterworth filter and numerically differentiated to calculate 2D velocity. The onset and end of each movement were determined as the point at which velocity crossed 10% of the peak velocity for each movement. In addition the endpoint had to represent 90% of the distance between the starting position and the target for the trial to be regarded as valid.

Angle at maximum velocity (*angle*) was calculated as the angular difference between a straight line from the start position to the target and the positional marker at maximum velocity (Sainburg and Wang 2002). For each participant, an average pre-adaptation (baseline) value was subtracted from all adaptation and post-adaptation trials.

For each participant a separate state-space model was applied to the *angle* data for the adaptation and post-adaptation phases to estimate an adaptation coefficient (Diedrichsen et al. 2005; Donchin et al. 2003; Thoroughman and Shadmehr 2000).

$$e(n) = p(n) - s(n) + E(n) \quad (1)$$

$$s(n+1) = s(n) + Ae(n) \quad (2)$$

The error on trial n is noted by e_n and is expressed as a function of the perturbation p_n , the internal state of the system s_n and noise (E_n). Equation 2 states that the internal state (s) changes by a certain proportion of the experienced error, where the amount of change is determined by the adaptation rate A . The matlab function *nfitlin* was used to estimate the free parameter A , in order to maximize the fit between observed and instructed errors.

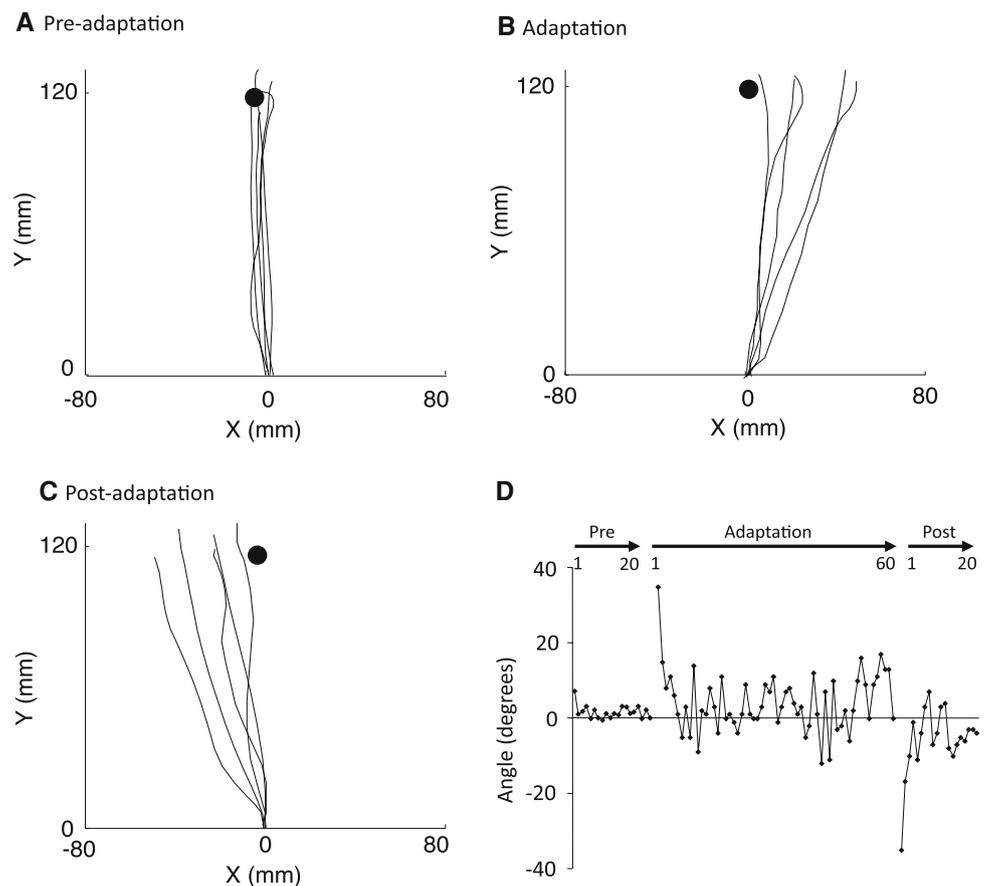
The adaptation rate (A) was used in a two-way between-subjects ANOVA comparing the factors TASK (step, gradual, none) and LOAD (shadowing, none). Note that the task manipulation refers to the task performed by the left hand, and the data analyzed are from the right hand. This allows us to assess the impact of TASK on step-adaptation performance within the right hand. Independent t tests were performed on all significant interactions. For the post-adaptation phase a Pearson correlation was performed which compared each participant's adaptation rate with their deadaptation rate within the post-adaptation phase. Data are expressed as mean \pm SEM, and effects were considered significant if $p \leq 0.05$.

Results

Summary

Figure 2 shows a typical participant's performance within the Rs– group. The pre-adaptation phase was characterized by fairly accurate performance (Fig. 2a). When initially exposed to the visual displacement the participant

Fig. 2 A typical performance within Rs−. Each line represents a right-hand movement towards the target (black solid circle). **a** Pre-adaptation phase characterized by straight trajectories. **b** Adaptation phase. The movements (CW 30° displacement) have an initial displacement to the right of the target. **c** Post-adaptation phase. Aftereffects are observed as errors in the opposite direction to the initial displacement. **d** Trial-by-trial performance



produced large errors in their movement (Fig. 2b, d). However, over subsequent trials participants adapted to the displacement and produced similar performance to baseline (Fig. 2d). When the displacements were suddenly removed, large aftereffects occurred in the opposite direction (Fig. 2c, d). The same pattern of performance was observed within all groups.

In our previous paper (Galea and Miall 2006), only end position error showed differences between alternating and unimanual performance. However, a pilot study of the current task revealed observable differences for end position error, average displacement error and angle at maximum velocity (*angle*). It is possible that within our previous study, where the movement was 30 cm, instead of 12 cm, angle at maximum velocity was not an appropriate or subtle enough a measurement due to the large amount of online correction which took place during the longer duration movement. Since Taylor and Thoroughman (2007) showed that dividing attention impaired motor adaptation but not online correction, we decided to concentrate on the feed-forward aspect of the movement which reflects the state of the internal model (Tseng et al. 2007) and therefore we focus our analysis on *angle*.

Pre-adaptation

The groups were compared across the last ten trials of the pre-adaptation phase for *angle*. A 3 (TASK: step, gradual, none) \times 2 (LOAD: shadowing, none) between-subjects two-way ANOVA was used to compare the average of these ten trials for each participant across the groups. Note that the task manipulation refers to the task performed by the left hand, and the data analyzed are from the right hand. The main effect of TASK [$F_{(2, 30)} = 0.4, p = 0.5$], LOAD [$F_{(1, 30)} = 0.005, p = 0.9$] and the interaction between TASK and LOAD [$F_{(2, 30)} = 0.005, p = 0.9$] were all non-significant (Rs− = $1.1^\circ \pm 1.3^\circ$, Rs+ = $1.1^\circ \pm 1.2^\circ$, RsLs− = $1.8^\circ \pm 1.1^\circ$, RsLs+ = $1.9^\circ \pm 1.1^\circ$, RsLg− = $1.6^\circ \pm 1.8^\circ$, RsLg+ = $2.0^\circ \pm 1.3^\circ$, mean \pm SEM). Thus, baseline performance across the groups was equivalent.

Adaptation

Each group's performance was characterized by a large initial error which was rapidly reduced over subsequent trials (Fig. 2d). For each participant, an average was calculated across the initial 60 trials of right-hand adaptation for total movement time, time to peak velocity and peak angular

velocity. Two-way between-subject ANOVAs [TASK(3) \times LOAD(2)] compared the right-hand performance across the six groups. There were no significant main effect of TASK [$F_{(2, 30)} < 1.6, p > 0.2$], LOAD [$F_{(1, 30)} < 0.05, p > 0.8$] or interaction between TASK and LOAD [$F_{(2, 30)} < 0.7, p > 0.4$] for total movement time (mean = 496 ± 40 ms), time to peak velocity (mean = 172 ± 22 ms) or peak velocity (mean = 0.52 ± 0.42 m/s).

The left and right hand's performance within the RsLs- and the RsLs+ group were compared using two separate repeated-measures ANOVAs [HAND(2) \times TRIAL(10)]. For both group comparisons, the main effect of HAND was not significant [each $F_{(1, 100)} < 2.8$, each $p > 0.09$], indicating similar adaptation across the left and right hands.

To assess adaptation, a state-space model (Eqs. 1, 2) was fitted to the individual participants' angle data (non-linear least squares fit, mean $R^2 = 0.58$). Figure 3a shows the predicted curves for a sample participant within each group while Fig. 3b shows the average adaptation rate (A, Eq. 2) for each group. A two-way between-subject ANOVA [TASK: step, gradual, none) \times LOAD (shadowing,

none)] compared the adaptation rate across the six groups. There was a significant effect for TASK [$F_{(2, 30)} = 41, p = 0.0005$], LOAD [$F_{(1, 30)} = 95, p = 0.0005$] and these factors interact [$F_{(2, 30)} = 5.3, p = 0.01$; Fig. 3b]. Independent t tests revealed that the rate of adaptation for the baseline group (Rs-: 0.71 ± 0.03 , mean \pm SEM) was significantly faster than the five other groups ($t_{(10)} > 3.6, p < 0.005$, one-tailed). Performing the baseline task with the right hand whilst gradually adapting in the left hand (RsLg-: 0.57 ± 0.02) lead to faster adaptation than when shadowing (Rs+, 0.28 ± 0.01 ; RsLg+, 0.22 ± 0.06 ; RsLs+, 0.06 ± 0.03) or switching between two opposing step-perturbations (RsLs-, 0.23 ± 0.05), ($t_{(10)} > 5, p < 0.001$, one-tailed). There were no significant differences between the remaining groups with just one additional cognitive demand (Rs+, RsLs-), or the group which switched between step and gradual and were exposed to the shadowing task (RsLg+; $t_{(10)} < 1.1, p > 0.3$, two-tailed). In the tasks with one additional cognitive demand (Rs+, RsLs- and RsLg-) and the task which involved two additional cognitive demands, however, one was switching

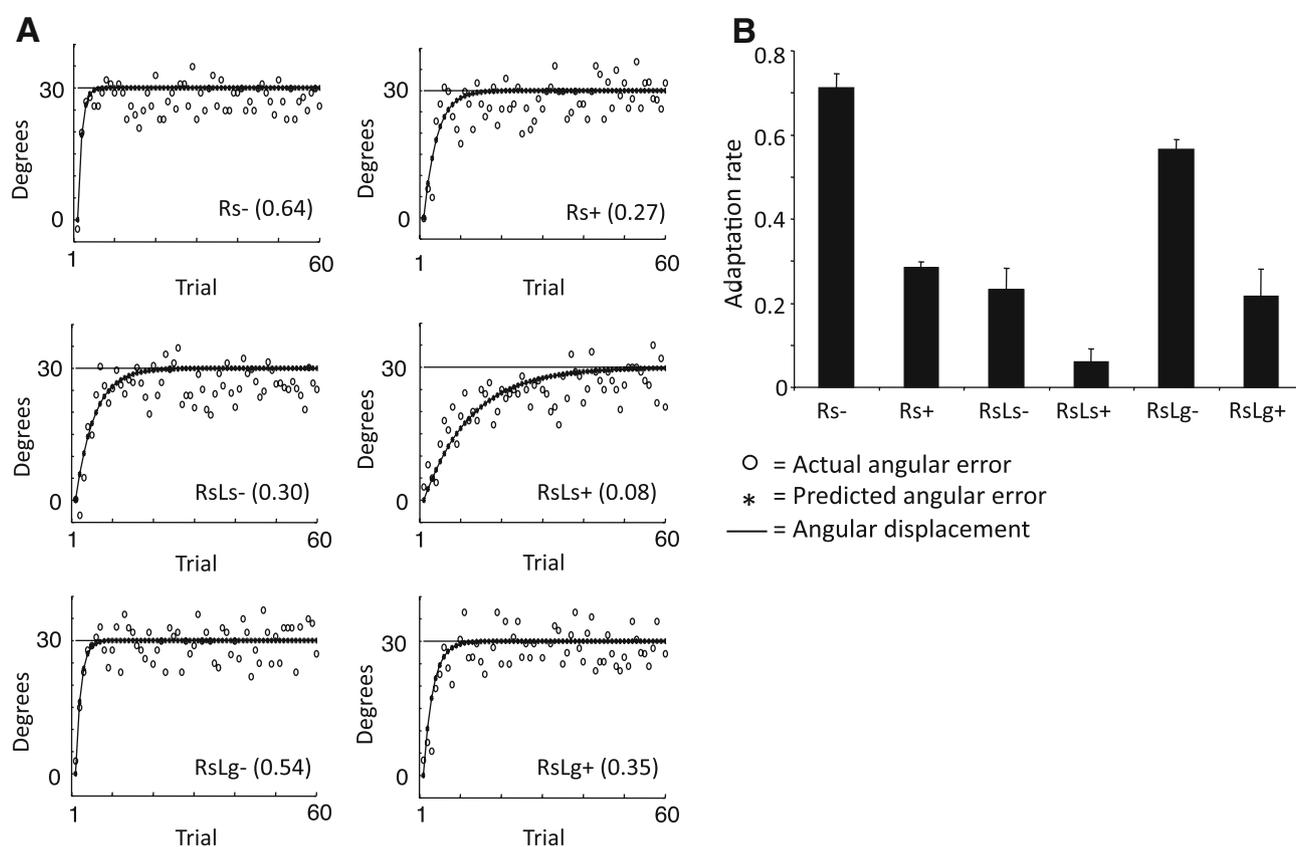


Fig. 3 Experiment 1: step adaptation. **a** Sample participant angle data for each group (circles) and the predicted curves from the applied state-space model (Eqs. 1, 2; black stars). The black line represents

the angular displacement. Numbers in brackets indicate the rate of adaptation. **b** Group averages for the rate of adaptation (A, Eqs. 1, 2) derived from the state-space model (mean \pm SEM)

between step and gradual adaptation (RsLg+) also lead to faster adaptation than when two additional cognitive demands were present (RsLs+; $t_{(10)} > 2.2$, $p < 0.05$, one-tailed).

The error rates for the secondary cognitive task were only recorded for the Rs+ and RsLs+ groups. This was taken as the number of words either missed or not correctly repeated by the participant. An independent t test revealed that the RsLs+ group exhibited significantly greater error than the Rs+ group (30 ± 3 vs. $17 \pm 2\%$, respectively; $t_{(10)} = 3.4$, $p = 0.003$).

Post-adaptation

For all groups post-adaptation was characterized by a large initial error which was corrected over subsequent trials (deadaptation; Fig. 2d). To assess the rate of deadaptation following the reintroduction of the veridical environment a state-space model (Eqs. 1, 2) was applied to the individual participant *angle* data (nonlinear least squares fit, mean $R^2 = 0.62$). The deadaptation rate (A) value was then correlated with the participant's adaptation rate, with the data being collapsed across groups, and a positive correlation was present ($r = 0.51$, $n = 36$, $p = 0.01$, two-tailed; Fig. 5a).

Discussion

The aim of Experiment 1 was to directly assess the effects of either a secondary resource switching or dividing task on adaptation to a single-step visual displacement. All groups adapted to the visual displacement and showed aftereffects in the post-adaptation phase suggesting that participants formed an internal model of the new sensorimotor transformation and were not simply performing a strategic adjustment (Bock et al. 2005).

As the Rs- group had a significantly faster adaptation rate than the other five groups, it is clear that the switching and dividing tasks had a detrimental effect on the speed at which participants adapt to a suddenly imposed visual displacement. As there were no significant differences between the adaptation rates of the Rs+, RsLs- and RsLg+ groups, it may be the case that the alternating motor task (switching) and secondary cognitive task (dividing) had a similar effect on performance. A combination of these tasks (RsLs+) had an additive detrimental effect on the rate of adaptation.

Gradual adaptation by one arm, used as a switching task within the RsLg- group, had only a slight detrimental effect on adaptation of the other arm. As a result the RsLg+ group behaved similarly to the groups challenged with dual tasks that required either switching between (RsLs-) or divided (Rs+) resources available to the

adaptation task. This suggests that gradual adaptation involved minimal cognitive resources (this is further explored in Experiment 2).

The RsLs+ group was exposed to a combination of switching (alternating task) and dividing (secondary cognitive task) tasks. The reduced adaptation rate in comparison to the Rs+ and RsLs- groups suggest that these processes had an additive effect on performance. Importantly, the RsLs+ group had significantly more errors within the secondary cognitive task than the Rs+ group. This supports the view that the alternating adaptation of both limbs demanded a greater amount of cognitive resources than unimanual adaptation. As only one arm was moving at any one time this is unlikely to be the result of the other limb acting like an additional dividing task and that the increase in error was a result of switching between the two adaptive states.

In direct contrast to the present results, Bock et al. (2005) found no significant difference between unimanual and alternating adaptation. However, because they only compared the groups at one time point it is possible that their measure of performance might not have been sensitive enough to assess differences in the rate of adaptation.

As noted above, there was a particularly interesting difference between the RsLg- group and the RsLs-, in that gradual adaptation within the opposite limb did not have the same detrimental effect as step adaptation. This may suggest that gradual adaptation does not require the same cognitive resources as step adaptation. We decided to explore this possibility further.

Experiment 2

Experiment 1 showed that step adaptation is a cognitively demanding process which can be negatively influenced by switching and dividing tasks. It has been proposed that step and gradual motor adaptation may occur at an explicit and implicit level of awareness, respectively (Hwang et al. 2006; Malfait and Ostry 2004). Additionally, gradual adaptation has been shown to occur when awareness is absent, supporting the notion that it is implicit (Ingram et al. 2000; Klassen et al. 2005; Malfait and Ostry 2004). However, Mazzoni and Krakauer (2006) showed that explicit information does not benefit the adaptation rate to a step-visual displacement. While this suggests that step adaptation may involve implicit processes, the present results clearly show that it can be negatively influenced by cognitively demanding secondary tasks. Thus, it is unclear whether gradual adaptation also requires resources which may be affected by cognitively demanding switching and dividing tasks.

Experiment 2 was similar to Experiment 1 but the right hand was always exposed to a gradual-visual displacement.

We hypothesize that if gradual adaptation occurs without a significant reliance on cognitive resources, then the addition of dividing and switching tasks should not affect the adaptation rate. However, if gradual adaptation requires substantial cognitive resources, despite the absence of awareness, then learning rates should be negatively influenced by the dividing and switching tasks.

Method

Participants

Thirty-six right-handed participants (19 female, mean age 22 ± 2 years) participated in the experiment. All participants signed a consent form and were either given course credit or money for their participation.

Materials, procedure and data analysis

The materials and general procedure were identical to the previous experiment. There were six new groups ($n = 6$) that adapted to a gradual displacement imposed on their right arm, which began at 0° and incremented by 0.25° per trial up to 30° . The displacement angle was then held at 30° for an additional 12 trials. Each active limb performed 132 trials during the adaptation phase. The six groups (Rg–, Rg+, RgLg–, RgLg+, RgLs–, RgLs+; Table 2) matched those of Experiment 1 except that they experienced gradual adaptation with their right arm instead of step adaptation.

The state-space model described in Eqs. 1, 2 was again applied to each participant's *angle* data. The estimated adaptation rate was used in a two-way between-subjects ANOVA comparing the factors TASK (gradual, step, none) and LOAD (shadowing, none). Note that the task manipulation refers to the task performed by the left hand, and the data analyzed are from the right hand. Independent *t* tests were performed on all significant interactions. For the post-adaptation phase a Pearson correlation was performed which compared each participant's adaptation rate with their deadaptation rate within the post-adaptation phase.

Results

Pre-adaptation

A 3 (TASK: gradual, step, none) \times 2 (LOAD: shadowing, none) between-subjects two-way ANOVA compared an average of the last ten trials of the pre-adaptation phase for each participant across the groups. The main effect of TASK [$F_{(2, 30)} < 2.7, p > 0.08$], LOAD [$F_{(1, 30)} < 0.03,$

$p > 0.8$] and the interaction between TASK and LOAD [$F_{(2, 30)} < 0.2, p > 0.5$] where all non-significant (Rg– = $0.9^\circ \pm 1.5^\circ$, Rg+ = $1.2^\circ \pm 1.3^\circ$, RgLg– = $0.8^\circ \pm 1.6^\circ$, RgLg+ = $2.1^\circ \pm 1.0^\circ$, RgLs– = $1.5^\circ \pm 1.3^\circ$, RgLs+ = $1.3^\circ \pm 1.4^\circ$, mean \pm SEM).

Adaptation

Each group's performance was initially characterized by a small amount of error which gradually increased across subsequent trials. Importantly, when asked at the end of the study if they noticed a visual displacement during the adaptation phase the Rg– and RgLg– groups reported no awareness of the perturbation.

For each participant, an average was calculated across the initial 122 trials of right-hand adaptation for total movement time, time to peak velocity and peak angular velocity. Two-way between-subject ANOVAs [TASK(3) \times LOAD(2)] compared the right-hand performance across the six groups. There were no significant main effect of TASK [$F_{(2, 30)} < 1, p > 0.3$], LOAD [$F_{(1, 30)} < 0.06, p > 0.7$] or interaction between TASK and LOAD [$F_{(2, 30)} < 1.1, p > 0.2$] for total movement time (mean = 480 ± 56 ms), time to peak velocity (mean = 163 ± 34 ms) or peak velocity (mean = 0.58 ± 0.22 m/s).

To assess adaptation, a state-space model (Eqs. 1, 2) was fitted to the individual participant *angle* data (nonlinear least squares fit, mean $R^2 = 0.52$). Figure 4a shows the predicted curves for a sample participant within each group while Fig. 4b shows the average adaptation rate (*A*: Eq. 2) for each group. A two-way between-subject ANOVA [TASK: step, gradual, none) \times LOAD (shadowing, none)] compared the adaptation rate across the six groups. There was a significant effect for TASK [$F_{(2, 30)} = 20, p = 0.001$], LOAD [$F_{(1, 30)} = 63, p = 0.001$] and interaction [$F_{(2, 30)} = 6.5, p = 0.004$; Fig. 4b]. Independent *t* tests revealed that the rate of adaptation for the baseline group (Rg–, 0.1 ± 0.01 ; mean \pm SEM) was significantly larger than all the other groups ($t_{(10)} > 4.4, p < 0.002$, one-tailed), except for switching between two gradual perturbations (RgLg–, 0.09 ± 0.004). This group was also faster than the tasks involving one additional cognitive demand (Rg+ 0.04 ± 0.003 ; RgLs–, 0.04 ± 0.005) or two additional cognitive demands (RgLg+, 0.04 ± 0.007 ; RgLs+, 0.02 ± 0.005 ; $t_{(10)} > 6.5, p < 0.002$, one-tailed). There were no significant differences between the groups which involved either a switching (RgLs–) or shadowing (Rg+) task or the group which involved a switching task between two gradual perturbations and a shadowing task (RgLg+; $t_{(10)} < 0.3, p > 0.7$). These three groups had a faster adaptation rate than the group which involved switching between a step and gradual perturbation and a shadowing task (RgLs+; $t_{(10)} > 2, p < 0.05$).

Table 2 Experiment 2 groups ($n = 6$)

Group ($n = 6$)	Pre-adaptation (20 trials for each active limb)	Adaptation (132 trials for each active limb)	Post-adaptation (20 trials for each active limb)
Rg–	Null	R = gradual CW	Null
Rg+	Null	R = gradual CW (+secondary task)	Null
RgLg–	Null	R = gradual CW L = gradual CCW	Null
RgLg+	Null	R = gradual CW L = gradual CCW (+secondary task)	Null
RgLs–	Null	R = gradual CW L = CCW	Null
RgLs+	Null	R = gradual CW L = CCW (+secondary task)	Null

For two groups the participants performed unimanual right-hand pointing movements independently (Rg–) or with an additional secondary cognitive task (Rg+). For the other two groups the participants performed alternating left- and right-hand pointing movements independently (RgLg–, RgLs–) or with an additional secondary cognitive task (RgLg+, RgLs+). Pre-adaptation consisted of movements under null conditions. The adaptation phase involved a 30° CW gradual-visual displacement for the right hand and, for the alternating groups, either a 30° gradual CCW displacement (RgLg–, RgLg+) or 30° step CCW displacement (RgLs–, RgLs+) for the left hand. During the post-adaptation phase all groups moved towards targets under null conditions, with no secondary cognitive task

In summary, the adaptation phase showed that the Rg– and RgLg– groups adapted at a faster rate than the four other groups. The gradual adaptation used as a switching task only had a marginal effect on adaptation and so the RgLg+ group had a similar adaptation rate to the two other groups exposed to either the switching or dividing task (Rg+, RgLs–). These were all faster than the RgLs+ group who were exposed to a step-adaptation switching task and dividing task.

Finally, we wanted to assess the adaptation rate for the left hand within the switching task which either involved gradual adaptation (RgLg–) or step adaptation (RsLg–) in the right hand. The adaptation rate for the left hand was significantly slower within the RsLg– group (0.05 ± 0.004) than the RgLg– group (0.08 ± 0.002 ; $t_{(10)} = 3.1$, $p = 0.01$). This suggests that during the switching task, step adaptation within the left or right hand significantly slowed the learning rate for gradual adaptation in the opposite hand.

Post-adaptation

To assess the deadaptation that occurred following the reintroduction of the veridical environment a state-space model (Eqs. 1, 2) was applied to the individual participant *angle* data (nonlinear least squares fit, mean $R^2 = 0.66$). The deadaptation rate (A) value was then correlated with the participant's adaptation rate with the data being collapsed across groups. A Pearson's correlation revealed a significant positive correlation ($r = 0.55$, $n = 36$, $p = 0.01$, two-tailed; Fig. 5b).

Discussion

The aim of this study was to assess how cognitively demanding secondary tasks influence the rate of adaptation to either a step- or gradual-visual displacement. We found that both were negatively influenced by a switching task, a shadowing task or a combination of both.

Previous research has proposed an explicit and implicit level of information processing within motor adaptation (Hwang et al. 2006; Malfait and Ostry 2004; Vangheluwe et al. 2005). Gradual adaptation has been shown to occur without awareness (Ingram et al. 2000; Klassen et al. 2005; Malfait and Ostry 2004) and thus is regarded as implicit. In contrast, step adaptation was thought to rely heavily on the use of high-level explicit (cognitive) information which is independent of the implicit, predictive changes in muscle activity (Criscimagna-Hemmingner et al. 2003; Malfait and Ostry 2004). However, Mazzoni and Krakauer (2006) showed that conflicting explicit information does not interfere with the adaptation rate to a step-visual displacement; suggesting that both step and gradual adaptation may actually be implicit.

The current results suggest a distinction between awareness and cognitive load during adaptation. There was a clear difference between step and gradual adaptation. Step adaptation invoked a large initial error which was quickly corrected for, whereas gradual adaptation involved small initial errors which steadily increased (because of incomplete adaptation). Step adaptation induced awareness of the perturbation whereas gradual adaptation did not. If cognitive load and awareness during adaptation depend

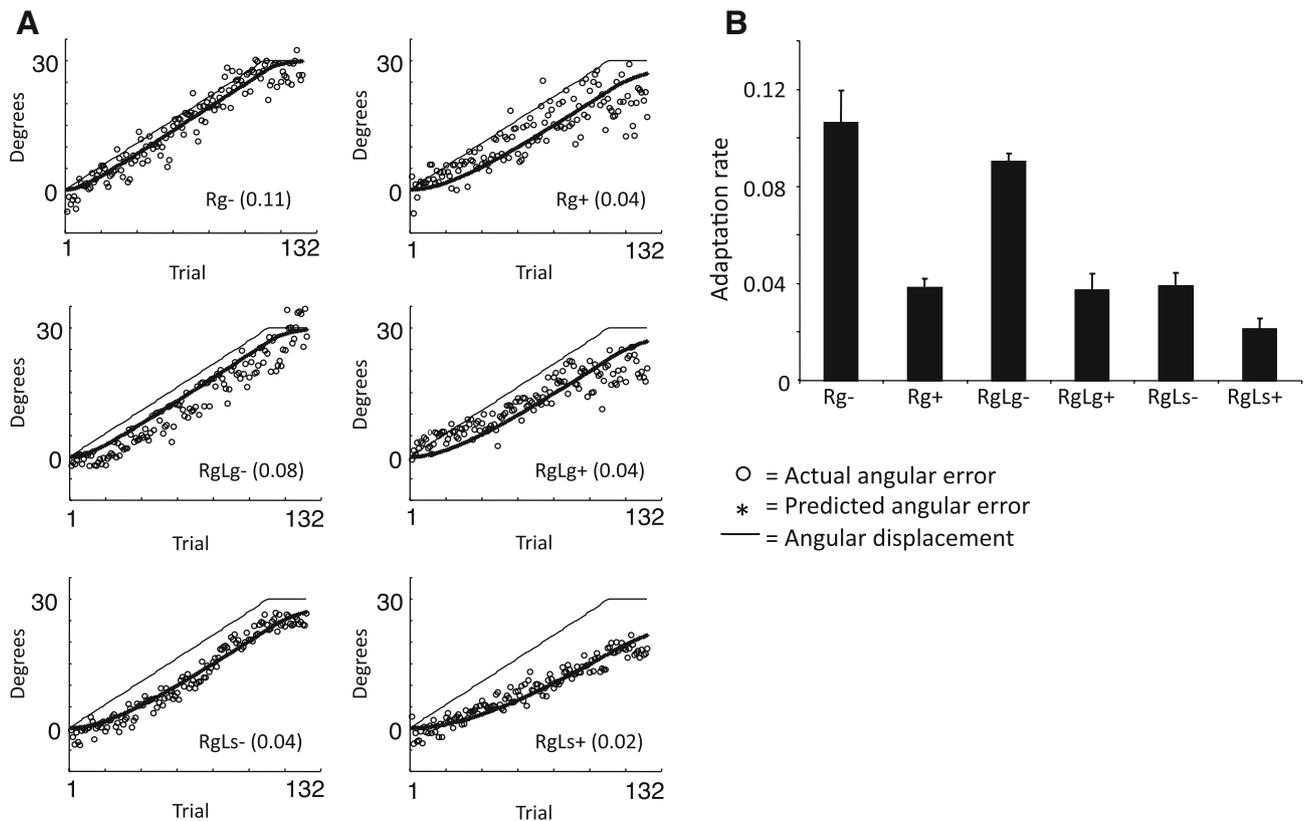


Fig. 4 Experiment 2: gradual adaptation. **a** Sample participant *angle* data for each group (*circles*) and the predicted curves from the applied state-space model (Eqs. 1, 2; *black stars*). The *black line* represents

the angular displacement. Numbers in brackets indicate the rate of adaptation. **b** Group averages for the rate of adaptation (*B*, Eqs. 1, 2) derived from the state-space model (mean \pm SEM)

A Experiment one: step adaptation

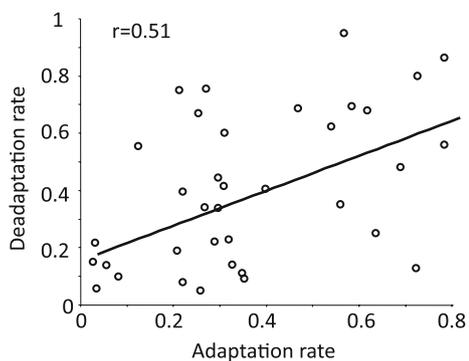
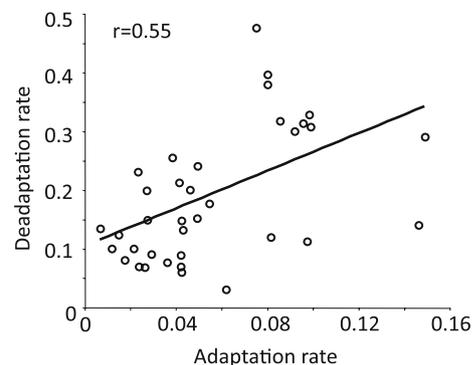


Fig. 5 Comparison of adaptation and deadaptation rate. **a** A positive correlation was found between the adaptation and deadaptation rate ($r = 0.51$) across all groups within Experiment 1. It is important to note that a slower deadaptation rate suggests better retention. **b** A similar positive correlation ($r = 0.55$) was observed across all groups

B Experiment two: gradual adaptation



within Experiment 2. Note the change in the y-axis and x-axis scale across figures, which shows that gradual adaptation generally adapted slower (smaller adaptation rate) and retained the information for longer (smaller deadaptation rate)

on the same underlying process then step adaptation should be negatively influenced by the switching and dividing task whereas gradual adaptation should not. However, as both forms of adaptation were negatively influenced by the

cognitively demanding secondary tasks, it suggests that each involves a resource-consuming cognitive component. Conversely, gradual adaptation within the switching task only had a minimal affect on adaptation rate indicating that

it does not consume substantial cognitive resources. It is possible that step adaptation may consume more of a common cognitive resource than gradual adaptation, with this resource also being used by the secondary cognitive task. Therefore, as step consumes a lot of this resource it interferes heavily with gradual adaptation, however, as gradual uses very little of this resource it only interferes slightly with step adaptation. To support this view we performed additional analysis on the left hand during the switching task and showed that step adaptation within either the left or right hand slows gradual adaptation to a large degree in the opposite limb but not vice versa. We propose that awareness and cognitive resource can be regarded as qualitatively different but that awareness may be a marker of the amount of resource required.

It must be noted that awareness was not quantitatively assessed across the two studies. However, when the Rg– and RgLg– groups were asked at the end of the study if they noticed a visual displacement during the adaptation phase they reported being unaware. The average error across the adaptation phase was 4° for the Rg– group; however, errors in the other groups were larger (RgLg+, RgLs–, RgLs+) so we cannot be certain participants remained unaware. Slachevsky et al. (2001) used a similar visual adaptation task where the displacement was increased by 1° per trial and asked the participants after each trial whether they were aware of the visual displacement. The authors found that participants remained unaware until approximately 30°. In our experiment, the angle was increased by 0.25° per trial, so we propose that gradual adaptation would have involved minimal awareness.

Finally, a slower deadadaptation rate in the post-adaptation phase would suggest better retention of the information learnt during the adaptation phase (Hadipour-Niktarash et al. 2007). The rate of adaptation and deadadaptation was correlated across both step and gradual adaptation. This implies that by increasing the cognitive demands of the task and as a result causing adaptation to take longer, the information was retained for longer during deadadaptation. This is consistent with evidence that gradual adaptation is more robust (Ingram et al. 2000; Klassen et al. 2005). This supports the view that the rate at which the initial adaptation is learnt directly influences retention (Smith et al. 2006). Smith et al. (2006) propose that motor adaptation depends on at least two distinct neural systems that retain information at different rates, namely a fast and slow system. They propose that information which is learnt more slowly will be retained for longer than information which is learnt faster. The present results support this idea and suggest that the adaptation-rate weighting system which affects retention can be manipulated by introducing task switching or dividing tasks during adaptation to a step or gradual-visual displacement.

In conclusion, the present study provides evidence that adaptation to a step or gradual-visual displacement can be disrupted with cognitively demanding secondary tasks. Importantly, step adaptation slows the learning rate of gradual adaptation to a large degree, whereas gradual adaptation only slightly slows the learning rate of step adaptation. This suggests that during the switching task these adaptation processes share a common cognitive resource. When gradual adaptation is being performed with step adaptation as the secondary task, step adaptation consumes a lot of cognitive resources. However, when gradual adaptation is the secondary task it has more limited cognitive resource demands, so only marginally influences the step-adaptation learning rate. Therefore, although gradual adaptation involves minimal awareness, it can still be disrupted with a cognitively demanding secondary task. We propose that awareness and cognitive resources can be regarded as qualitatively different but that awareness is possibly a marker of the amount of resources allocated to a task.

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