The role of motor imagery in learning via instructions

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Abstract

Learning via instructions and learning through physical practice are complementary pathways to obtain skilled performance. Whereas an initial task representation can be formed on the basis of instructions, physically practicing novel instructions leads to a shift in processing mode from controlled processing toward more automatic processing. This shift in processing mode is supposedly caused by the formation of a pragmatic task representation, which includes task parameters needed to attain skilled task execution. In between learning via instructions and physical practice, a third type of learning can be situated, motor imagery. Two experiments are reported that studied the extent to which motor imagery can enhance the application of novel instructions. A procedure was developed in which performance improvement after motor imagery could be measured for behavioral markers of processes underlying response selection (i.e., initiation time of a response sequence) and for behavioral markers of processes underlying movement execution (i.e., completion time of the response sequence). Our results suggest that whereas physical practice improves response selection and movement execution, motor imagery only improves response selection. We propose that motor imagery also leads to a shift in processing mode and to the formation of a pragmatic task representation, albeit a less detailed one as compared to the representation that is formed on the basis of physical practice.

The role of motor imagery in learning via instructions

Many people have learned complex skills such as handling computers, cameras and cell phones. In most cases these skills are largely based on instructions, which are provided by manuals or peers. An important advantage of instructions is that they offer a quick route to learning. In contrast to trial-and-error learning in which contingencies are learned gradually over time, learning through instructions appears to be instant (e.g., De Houwer, Beckers, Vandorpe, & Custers, 2005; Liefooghe, Wenke, De Houwer, 2012; Meiran et al., 2015; Cohen-Kdoshay & Meiran, 2007; Wenke, Gaschler, & Nattkemper, 2007). Daily life functioning, however, is not uniquely based on the implementation of instructions alone. Novel instructions will most often be physically practiced before skilled behavior emerges. In some cases, practice can be physical with an instruction being executed overtly several times (i.e., physical practice or PP). However, practice does not necessarily need to be overt and people can engage in a more covert modus of practice, which is not associated with physical movement. Such type of practice is often referred to as motor imagery (MI). While the effect of PP on the application of novel instructions has been documented in a number of studies (e.g., Ruge & Wolfensteller, 2010), not much is known about the impact of MI in this context. Accordingly, the aim of the present study is to investigate the effect of MI and PP in the application of novel instructions.

Instructions and Physical Practice

Ever since the seminal work of Schneider and Shiffrin (1977), physical practice is considered as the prime gateway to automaticity. In recent years, however, an increasing amount of research suggests that novel instructions specifying S-R mappings (e.g., De Houwer et al., 2005; Liefooghe et al., 2012; Meiran et al., 2015; Cohen-Kdoshay & Meiran, 2007; Wenke, et al., 2007), but also instructions specifying response-effect contingencies (Theeuwes, De Houwer, Eder, & Liefooghe, 2015) and even No-Go instructions (Liefooghe, Degryse, & Theeuwes, 2016) can also lead to automatic effects. The common hypothesis is that instructions are implemented into a procedural representation, which is kept active in working memory (e.g., Liefooghe et al., 2012; Meiran, Cole & Braver, 2012) and guides future task execution, possibly by enabling prepared reflexes (e.g., Meiran et al., 2015).

Ruge and Wolfensteller (2010) propose that the representation formed on the basis of instructions is rather abstract in nature and only includes conceptual stimulus and response codes (see also Liefooghe et al., 2012; Tibboel, Liefooghe, & De Houwer, 2016; Wenke et al., 2007, for similar conclusions). This abstract representation supposedly controls initial performance. The PP of novel instructions, however, is assumed to lead to the formation of a second representation, which the authors label as a pragmatic task representation. This representation is supposed to be more finegrained than the initial representation and includes various parameters that underlie the skilled execution of a task. Evidence for this account comes from a neuro-imaging experiment in which novel S-R mappings were practiced a number times and modulations in behavioral performance and brain activity were measured. Ruge and Wolfensteller (2010) observed that behavioral improvement was associated with a shift in brain activity, such as a decrease in the left inferior junction and an increase in the basal ganglia, more specifically in the caudate nucleus. Such pattern suggests a reduced involvement of executive control following PP. Interestingly, the shift in brain activity started from the very first trial on which the novel S-R mappings had to be applied. Furthermore, Ruge and Wolfensteller (2010) observed that a stronger activation in the lateral pre-motor cortex and prefrontal cortex during the encoding of the novel S-R mappings, predicted enhanced performance improvement during the training phase. This finding led to the suggestion that the formation of a pragmatic task representation can be initiated even before PP, on the basis of MI. As such, the implementation of novel instructions into the actions they specify, may be driven by MI of these instructions.

Ramamoorthy and Verguts (2012) introduced a computational model, which specifies how pragmatic task representations are formed on the basis of PP. Their model supposes the presence of two processing routes. The first route quickly learns novel S-R associations on the basis of instructions, but leads to slow responding. The second route slowly learns novel S-R associations, but elicits fast responses. Ramamoorthy and Verguts (2012) propose that the second route learns S-R associations on the basis of Hebbian learning, following the application of these S-R associations through the first route. Initial task performance is mainly under control of the slow route, with the fast route gradually taking over control after sufficient PP. Simulations indicated that the model of Ramamoorthy and Verguts (2012) is able to account for the results of Ruge and Wolfensteller (2010), but also for other findings such as the instruction-based congruency effect reported by Waszak, Wenke, and Brass (2008) as well as the dissociation between instruction understanding and instruction following (e.g., Duncan, Emslie, & Williams, 1996; Luria, 1966).

The study of Ramamoorthy and Verguts (2012) as well as the study of Ruge and Wolfensteller (2010) support the conclusion that the application of novel instructions quickly improves through PP and that this improvement is underlain by a shift in processing mode. The initial application of instructions is based on an abstract representation, which guides behavior in a slow and controlled manner. PP leads to the formation of a pragmatic task representation and therefore fast processing, which guides behavior in a quick and automatic way. The central question in the present study is whether such shift in processing can be obtained on the basis of MI, which would strengthen the hypothesis that MI is part of the implementation of novel instructions.

Motor Imagery

MI has received much attention in the past decades (see Guillot & Collet, 2008; McAvinue & Robertson, 2008; Schuster et al., 2011; van Meer & Theunissen, 2009 for reviews). Richardson (1967, p. 95) defines MI as “the symbolic rehearsal of a physical activity in the absence of any gross muscular movements”. Thus, MI is based mainly on the mental simulation of an action under training conditions in which the actual execution of that action is minimal or absent. Although MI is (more) covert in nature, it shares features with PP. Most importantly, it has been found that the time needed to perform a particular action covertly covaries with the time needed to execute an action overtly (e.g. Decety & Michel, 1989; Decety, Jeannerod, & Prablanc, 1989). For instance, Decety et al. (1989) observed that increasing the length of a particular walking distance, not only increases the actual walking time but also the imagined walking time. Neuro-physiological research also demonstrates that overt and covert actions do share similar neural substrates, which led to the hypothesis that covert and overt actions are part of the same continuum, with overt actions being based on covert actions, without covert actions being necessarily translated into overt actions (e.g. Jeannerod, 2001).

In view of the similarity between PP and MI, it is not surprising that beneficial effects of MI have been reported in the acquisition of complex skills, such as typing (Nyberg, Eriksson, Larsson & Marklund, 2006; Wohldmann, Healy, & Bourne, 2007; 2008), playing music (e.g., Highben & Palmer 2004; Lim & Lippman, 1991), or even surgical interventions (e.g., Rogers, 2006). However, the extent by which MI improves performance in comparison to PP remains unclear. Whereas it has been asserted that the beneficial impact of MI on performance is smaller than the impact of PP (see Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983 for meta-analyses), other research demonstrated that the effect of MI and PP is equally large and under certain training conditions MI can be even more beneficial than PP (e.g., Wohldmann, Healy, & Bourne, 2008). Finally, several studies reported that the influence of MI on performance improvement is minimal or even absent (e.g., Corbin, 1967; Shanks & Cameron, 2000; Shick, 1970; Smyth, 1975). These diverging findings are caused by the use of different tasks.

Besides the type of task, the type of performance improvement that is measured within a task also seems of importance. Wohldmann et al. (2007, see also Wohldmann et al., 2008) argued that more finegrained measures of performance, which separate markers of stimulus encoding and response selection from markers of movement execution, are essential in clarifying how MI improves performance. These authors compared the impact of MI and PP in a digit data-entry task. In such task, participants enter strings of three digits on a computer keyboard. The time needed to enter the first digit is considered as a proxy of stimulus encoding and response selection (i.e., reaction time), whereas the average speed of the subsequent keystrokes is considered as a proxy of movement execution (i.e., movement time, see also Brown & Carr, 1989; Buck-Gengler & Healy, 2001; Fendrich, Healy, & Bourne, 1991 for similar distinctions). In the studies of Wohldmann et al. (2007, 2008) a test phase followed either a training phase consisting of PP or a training phase consisting of MI. Interestingly, these authors observed that MI modulated performance to the same degree as PP. More precisely, practice (PP and MI) reduced the movement time but not the reaction time, which sometimes even increased after practice. The reduction in movement time suggests that MI improves processes related to movement execution. However, the reaction time is more difficult to interpret. On the one hand, this result suggests that MI (as well as PP) does not improve response selection. On the other hand, as Wohldmann and colleagues argue, the reaction time may have been inflated by a shift in encoding strategy. In the early stage of practice, each digit of a string may be encoded and responded to separately. After some practice, participants may encode the digits of a string as one chunk. As a result, stimulus encoding becomes centralized prior to the first key-press, which increases the reaction time and decreases the movement time.

The Present Study

Although MI has been investigated extensively in the context of skill acquisition, relatively little is known about the effects of MI on the application of novel instructions. More specifically, it is not yet clear whether MI can improve the application of new instructions as it is the case for PP (Ruge and Wolfensteller, 2010). Such modulation would suggest that MI can also lead to a quick shift in processing mode. The first aim of the present study was to put this hypothesis at test. In addition, inspired by the proposals of Wohldmann et al. (2007, 2009) we further investigated whether MI leads to the improvement of response selection, movement execution, or both.

The present study compared performance after merely implementing newly instructed S-R mappings, performance after the implementation of novel S-R mappings complemented with PP, and performance after the implementation of novel S-R mappings complemented with MI. In order to dissociate between response selection and movement execution, we used complex S-R mappings in which a stimulus was assigned to a sequence of letters that had to be typed on a keyboard (e.g., “if you see the picture of a bridge, press the sequence a-z-e on the keyboard”). In line with the work of Wohldmann et al. (2007, 2008), performance on the first response of a response sequence was considered as a proxy of response selection. In contrast, performance on the subsequent responses was assumed to reflect movement execution.

Our procedure was composed of different runs of trials each consisting of a training and a test phase. Each run started with the presentation of two novel S-R mappings, followed by a training phase. After the training phase, the instructions were presented for a second time, before a test phase started. In the test phase, each S-R mapping was probed only once. The nature of the training phase varied depending on the training condition participants were assigned to. In the PP condition, participants practiced each S-R mapping for ten trials. On each trial, a stimulus was presented and the corresponding response sequence had to be typed. Importantly, a home-key was used, namely the spacebar of the keyboard. Between each typing response, participants had to place their typing-finger back on the home-key. In the MI condition, the same sequence of events occurred, but participants were instructed to mentally imagine that they typed a letter. Participants were instructed to release the home-key, imagine to type the required letter and press the home-key again after the imagined movement was completed. The use of inter home-key intervals permitted us to compare the time needed to perform imagined and actual typing movements in the training phase (i.e., a mental-chronometry procedure, see Guillot et al., 2012 for a review). As such, it was possible to assess whether actual and imagined typing times were in the same range (e.g., Decety & Michel, 1989). Finally, concerned by previous reports suggesting that participants may not engage in MI (e.g., Shanks & Cameron, 2000), a manipulation check was added. Based on the observation that actual walking times and imagined walking times are both prolonged by the walking distance (Decety et al., 1989 see also Guillot & Collet, 2005 for a review of similar findings), we constructed two types of response sequences. Namely, response sequences comprising responses that were physically close to the home-key (i.e., close response sequences) and response sequences comprising responses that were located further away from the home-key (i.e., distant response sequences). The observation of different inter home-key intervals for close and distant sequences in the MI condition thus offered an additional indication that participants were involved in MI during the training phase as was intended by our procedure.

The PP and MI conditions were compared with a "no practice" (NP) training condition, in which no practice was possible in the training phase. In the NP condition, only partial S-R mappings were instructed at the beginning of the run (e.g., if "bunny", press ?-?-?). Participants thus were only given the relevant stimuli. In line with the PP and MI condition, the "training" phase in the NP condition consisted of repeated presentations of the stimuli and participants were simply required to press the home-key three times in a row before the next stimulus could appear. In other words, participants in the NP condition experienced the same sequence of events as in the PP and MI condition, but did not have any knowledge about the actual S-R mappings. The actual S-R mappings in the NP condition were provided at the onset of the test phase.

On the basis of the aforementioned procedure, we addressed two main questions on the effect of MI in the application of novel instructions. First, does MI enhance the application of newly instructed S-R mappings? Second, does MI modulate response selection, movement execution, or both?

Experiment 1

Method

Participants and Design. Twenty-four students at Ghent University participated for course requirements or payment of 20 EURO. Participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. All participants signed an informed consent and the experiment followed the ethical guidelines of Ghent University. Each participant performed the NP, PP, and MI condition in three different blocks. On each run, one S-R mapping comprised a close response sequence and the other S-R mapping comprised a distant response sequence. Taken together, a 3 (Training Condition: PP, MI, NP) by 2 (Phase: Training, Test) by 2 (Sequence Type: Close, Distant) design was used with repeated measures on all three factors.

Materials. A choice-reaction task was used in which participants had to respond to a picture by entering a particular response sequence. The pictures were selected from the Snodgrass and Vanderwart (1980) picture set. Based on the Dutch-naming ratings of these pictures by Severens, Van Lommel, Ratinckx, and Hartsuiker (2005), 186 pictures were selected with a naming-agreement rating of at least 70%. These pictures depicted an object or an animal that could be named with a word consisting of maximally six letters. The names of the used pictures are presented in Table 1. Based on this set, 93 pairs of stimuli were created. In each pair, one stimulus was assigned to a distant response sequence. The other picture was assigned to a close response sequence. Close and distant response sequences were constructed on the basis of two sets of letter-keys of an AZERTY keyboard that differed in their physical distance from the spacebar, which served as the home-key (see Figure 1a). For the distant response sequences, the responses were selected from the letter-keys “a”, “z”, “e”, “r”, “t”, “y”, and “u”. For the close response sequences, the responses were selected from the letter-keys “w”, “x”, “c”, “v”, “b”, “n”, and “f”. The close and distant response sequences always consisted of three letters, randomly selected from the corresponding set of letter-keys. New stimuli and response sequences were used in each run and they were never reused across different runs. The 93 pairs of S-R mappings were randomly assigned to either the PP, MI, or NP condition. Within each training condition, one pair was used for familiarization and the remaining 30 pairs were used for actual measurement.

In each training condition, a run started with the presentation of two S-R mappings. These S-R mappings only included the picture names (e.g., If “bridge”, press a-z-e; if “table”, press w-x-c), whereas the actual pictures were used during the training and test phase. The presentation of the S-R mappings was followed by the training phase. In the training phase of the PP condition, each S-R mapping was physically practiced for 10 times in a random order. On each trial, a picture appeared on the screen and the corresponding response sequence had to be entered on the keyboard. To this end, participants could only use their right index finger. At the onset of a response sequence, participants were required to keep the spacebar pressed down. They released the spacebar to press the first letter-key and returned to the spacebar. This sequence of events was repeated for the second and the third letter-key. For instance, when required to enter the sequence a-z-e: (a) participants released the spacebar, pressed the “a”, pressed the spacebar; (b) released the spacebar, pressed the “z”, pressed the spacebar; and (c) released the spacebar, pressed the “e”, pressed the spacebar. Participants were instructed to keep the spacebar pressed down until the next trial. When pressing a letter-key, the corresponding letter appeared on the screen (see Figure 1b). If the entered letter was correct, it was displayed in black, otherwise it appeared in red. After an incorrect response sequence, the message “FOUT” (“Wrong” in Dutch) was presented accompanied by the correct response sequence for 500ms. After the training phase, the S-R mappings were presented for a second time. Finally, the test phase started. The test phase in the PP condition was identical to the training phase, but now each S-R mapping was probed only once in a random order.

In the training phase of the MI condition, participants also used the home-key but entered each letter-key mentally. In other words, when required to enter the response sequence a-z-e mentally: (a) participants released the spacebar, imagined they pressed the "a", pressed the spacebar; (b) released the spacebar, imagined they pressed the "z", pressed the spacebar; and (c) released the spacebar, imagined they pressed the "e", pressed the spacebar. When a letter-key was pressed physically, an error message was presented stating "De toetsen niet indrukken!" ("Do not press the keys!", in Dutch). In order to maximize the similarity with the PP condition, the letter that had to be entered according to the instructed S-R mappings, appeared on the screen when the spacebar was pressed down after each imagined movement. Following the training phase, the instructions were presented a second time before the test phase started. In the test phase, participants entered the letter-keys physically as in the PP condition.

At the onset of a run in the NP condition, no response sequences were instructed. Each S-R mapping only referred to a string of question marks (e.g., if "bridge" press ?-?-?). In the training phase, participants were presented with each picture for 10 times in a random order and they were instructed to press the home-key three times in a row each time a stimulus appeared. After each keystroke a question mark appeared on the screen (see Figure 1c). After the training phase, the complete S-R mappings were provided (e.g., if "bridge" press a-z-e). This instruction screen was followed by the test phase, which was the same as in the other two training conditions.

The S-R mappings were always presented centrally on the screen, the S-R mappings referring to the close and distant response sequences were ordered randomly one above the other. S-R mappings and feedback messages were presented in Arial font, size 24. Participants had a maximum deadline of 10 seconds to enter a complete response sequence.

Procedure. Participants were tested individually by means of a personal computer with an Intel Core Duo E8600 and a 17-inch color monitor attached to it. The experiment was programmed by using Tscope, a free C/C++ library for running psychological experiments (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006) . At the beginning of the experiment, participants were presented with a cover story, which created the illusion that we monitored the amount of effort they put into making imagined typing movements.

Participants were told that the muscle activation in their right index finger was monitored by using a measurement device (i.e., a defected EEG amplifier) and that imagining an action led to small muscle activation. This activation was measured to control whether participants did perform the imagined movements. Therefore, an electrode, which was wired to the device, was taped onto their right hand (all responses had to be made with the right index finger). In a so-called calibration phase, participants were asked to go from the home-key to one of two letter-keys ("a" or "p") and back. In a next step, participants were asked to imagine doing these movements. The electrode remained on the participants' hand during the whole experiment. The experimenter was also present during the entire experiment, pretending to monitor participants' MI performance on a second computer to which the measurement device was attached.

After the calibration phase, the instructions of the experiment were presented on screen and paraphrased if necessary. The three training conditions (PP, MI, and NP) were administered in three different blocks, which were counterbalanced across participants. Each training condition started with an instruction screen, informing participants about the type of practice (PP, MI, or NP). At the start of each training condition, the first run served as familiarization, during which participants were monitored and additional information was provided if necessary. This run was followed by six blocks of five runs with a small break after each block.

Each run started with the presentation of two S-R mappings. In the PP and MI condition, the S-R mappings referred to response sequences (e.g., If "bridge" press a-z-e; if "table" press w-x-c). In the NP condition, the S-R mappings referred to question marks (e.g. If "bridge" press ?-?-?; if "table" press ?-?-?). After pressing the spacebar or a maximum time of 40 seconds, the instructions were removed and the training phase started. The training phase consisted of 20 practice trials, 10 trials for each S-R mapping. After completing the training phase, the S-R mappings were presented for a second time, following the same parameters as the first presentation. Finally, the test phase started, which consisted of two trials, one for each S-R mapping. The interval between the last response of a response sequence and the next stimulus onset was 750ms. For an outline of the procedure see Figure 3. The experiment lasted for approximately two hours.

Results

Training phase. The length of the inter-home key intervals was the only dependent variable that was common to the training phases of the three training conditions. The inter home-key interval of the first response was considered as a proxy of response-selection processes and the average length of the inter home-key intervals of the two subsequent responses was considered as a proxy of movement-execution processes. The length of the inter home-key interval of the first response was defined as the time between the stimulus onset and the first time participants pressed down the home-key after releasing the home-key in order to physically or mentally enter the first letter-key. For the subsequent responses, the length of the inter-home key interval was defined as the time between pressing down the home-key after having entered the previous letter-key and pressing down the home-key after having entered the current letter-key (see Figure 4). For each run, the average length of the second and third inter-home key interval was calculated. When trimming the data, errors were not discarded from the PP condition, because no error data was available from the training phases of the NP and the MI condition. For each participant, inter home-key intervals longer than 2.5 SDs of each cell mean of the design were excluded. This resulted in a data loss of 2% for the first response and 3% for the subsequent responses. The length of the inter home-key intervals was investigated separately for the first response and the subsequent responses by using two crossed linear mixed effects model analyses as implemented in the R package “lme-4” (Bates, Mechler, Bolker & Walker, 2012). Linear mixed effects models were used in order to capture the variance accounted for by the use of randomly created response sequences. The use of such models is widespread in psychology, ranging from topics in psycholinguistics (e.g., Baayen, Davidson, & Bates, 2008; Jaeger,

2008) to topics in social psychology (e.g., Judd, Westfall, & Kenny, 2012). Because the different response sequences were created randomly, some sequences were easier to chunk and execute than other sequences. To account for this variability, the different strings of letter-keys (e.g., a-z-e) were considered as a random-effect factor and entered in the linear mixed effect model as a random intercept. Similarly, participants were also considered as a random-effect factor, thus accounting for individual differences with respect to handedness and typing skills. Both random factors were fully crossed. Sequence Type (close sequence, distant sequence) and Training Condition (PP, MI, NP) were considered as fixed effect-coded factors. In principle, the type of response (first response, subsequent responses) could also be entered as a fixed effect, but for reasons of clarity we preferred to treat both types of responses in a separate analysis. The reported *p*-values for the fixed effects are based on a Type III ANOVA using a χ^2-distribution as implemented in the R package "car" (Fox & Weisberg, 2011). Contrasts were calculated by using dummy coding. The mean length of the inter home-key intervals and corresponding standard deviations of each cell of the design are presented in Table 2 . It should be noted that the distinction between close and distant response sequences in the training phase of the NP condition is artificial, because participants were not instructed with the complete S-R mappings in the training phase of that condition. The distinction is based on the complete S-R mappings, which were presented after the training phase, at the onset of the test phase.

First response. The main effect of Training Condition was significant, $\chi^2(2)=$ 44142.84, $p<.001$. Inter-home key intervals were significantly longer in the PP condition ($M=$ 1229ms, 95% CI [1171, 1286]) than in the MI condition ($M=$ 992ms, 95% CI [934, 1049]), $\chi^2(1)=$ 3274.85, $p<$ .001, $[\Delta z]=$ .47[1], and the inter-home key intervals were significantly

[1] $[\Delta z]$ refers to the absolute difference between estimated means expressed in z-scores and offers a simple indication of the effect size of a particular contrast. $[\Delta z]$ is obtained by z-transforming reaction times and subsequently fitting the linear mixed effects model of interest on these z-values. As such, estimated cell means expressed in z-scores are obtained. $[\Delta z]$ is then calculated by taking the absolute difference between the relevant estimates. Such approach can only be applied to reaction times. Because error rates have a binomial

longer in the MI condition than in the NP condition (M= 384ms, 95% CI [327, 441]), $\chi^2(1)$= 21544.48, p< .001, [Δz]= 1.19. The main effect of Sequence Type was not significant, χ^2<1.

The interaction between Training Condition and Sequence Type was significant, $\chi^2(2)$= 24.67, p< .001. In the PP condition, the inter-home key interval was significantly shorter for close response sequences (M= 1216ms, 95% CI [1158, 1274]) than for the distant response sequences (M= 1242ms, 95% CI [1184, 1300]), $\chi^2(1)$= 7.84, p<.01, [Δz]= .05. The effect of Sequence Type was neither significant in the MI condition, $\chi^2(1)$= 2.06, p= .151, nor in the NP condition, χ^2< 1.

Subsequent responses. The main effect of Training Condition was significant, $\chi^2(2)$= 24108.18, p< .001. Inter-home key intervals were significantly longer in the MI condition (M= 679ms, 95% CI [633, 724]) compared to the PP condition (M= 547ms, 95% CI [502, 593]), $\chi^2(1)$= 2721.89, p< .001, [Δz]= .47, and significantly shorter in the NP condition (M= 292ms, 95% CI [247, 338]) compared to the MI condition, $\chi^2(1)$= 23356.58, p< .001, [Δz]= 1.36. The main effect of Sequence Type was also significant, $\chi^2(1)$= 23.45, p< .001. Inter-home key intervals were shorter for the close response sequences (M= 492ms, 95% CI [446, 538]), than for the distant response sequences (M= 520ms, 95% CI [474, 565]), [Δz]= .10.

The interaction between Training Condition and Sequence Type was significant, $\chi^2(2)$= 160.27, p< .001. The length of the inter-home key intervals in the PP condition was shorter for the close response sequences (M= 516ms, 95% CI [470, 562]) than for the distant response sequences (M= 579ms, 95% CI [533, 625]), $\chi^2(1)$= 96.20, p< .001, [Δz]= .22. In the MI condition, the inter-home key intervals were also shorter for the close response sequences (M= 669ms, 95% CI [623, 715]) than for the distant response sequences (M= 689ms, 95% CI [643, 735], $\chi^2(1)$= 9.16, p< .01, [Δz]= .07. In the NP condition, the effect of Sequence Type was not significant, χ^2< 1.

distribution, z-transformation is not possible.

Test phase. Several dependent measures were common to the test phases of all three training conditions. The inter home-key intervals could now be divided into two components: the actual response times and the return times. The actual response time was the time needed to enter a particular letter-key. For the first response, this is the time between the stimulus onset and pressing down the first letter-key of the response sequence. For the subsequent response keys, this is the time between pressing down the home-key after the previous letter-key was entered and pressing down the current letter-key. The return time was the time needed to return from a particular letter-key to the home-key. An illustration of these different timing components is presented in Figure 3. Finally, error rates could also be measured in all three training conditions. As for the training phase, the measures of the second and the third response were averaged. When trimming the data, errors were now excluded. Only response sequences that were completely correct were included. This resulted in a data loss of 12%. For each timing component, outliers were identified in the same way as in the training phase. An additional 3% of the inter home-key intervals and actual response times were considered as an outlier. Means and corresponding standard deviations of each cell of the design are presented in Table 2. It could be argued that the use of two trials in the test phase (i.e., one probe for each mapping) could bias the measurement of performance improvement following PP, MI, and NP. The test phase consisted of two trials with each trial probing one of the two instructed S-R mappings. As such, the identity of the S-R mapping probed on the second trial could be inferred, once the first trial was completed. Accordingly, performance on the second trial of the test phase may benefit from additional preparation processes and aggregating across both trials may result in a biased pattern of results. In order to account for this possibility, performance in the test phase was also analyzed by only including the first trial of the test phase. This analysis is briefly presented in Appendix A and converges with the main findings.

Inter Home-Key Intervals.

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 507.24$, $p< .001$. The length of the inter-home key intervals was significantly shorter in the PP condition ($M= 1074$ms, 95% CI [974, 1174]) than in the MI condition ($M= 1359$ms, 95% CI [1258, 1459]), $\chi^2(1)= 237.96$, $p< .001$, $[\Delta z]= .51$, and significantly shorter in the MI condition than in the NP condition ($M= 1496$ms, 95% CI [1395, 1597]), $\chi^2(1)= 49.21$, $p< .001$, $[\Delta z]= .24$. The main effect of Sequence Type was also significant, $\chi^2(1)= 9.42$, $p< .01$, $[\Delta z]= .09$. Inter-home key intervals were shorter for close response sequences ($M= 1271$ms, 95% CI [1172, 1370]) than for distant response sequences ($M= 1319$ms, 95% CI [1219, 1418]). The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2)= 1.95$, $p= .377$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)= 519.93$, $p< .001$. Inter-home key intervals were significantly shorter in the PP condition ($M= 526$ms, 95% CI [1219-14181) than in the MI condition ($M= 637$ms, 95% CI [594, 679]), $\chi^2(1)= 369.12$, $p< .001$, $[\Delta z]= .58$. The MI condition and the NP condition did not differ significantly, $\chi^2(1)= 2.47$, $p= .116$, $[\Delta z]= .05$. The effect of Sequence Type was also significant, $\chi^2(1)= 148.69$, $p< .001$, $[\Delta z]= .37$. Inter-home key intervals were shorter for the close response sequences ($M= 563$ms, 95% CI [521, 605]) than for the distant response sequences ($M= 635$ms, 95% CI [593, 677]). The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2)= 2.40$, $p= .302$.

Actual Response Times.

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 423.94$, $p< .001$. Actual response times were significantly shorter in the PP condition ($M= 826$ms, 95% CI [737, 915]) than in the MI condition ($M= 1045$ms, 95% CI [956, 1134]), $\chi^2(1)= 168.81$, $p< .001$, $[\Delta z]= .44$. Actual response times were significantly shorter in the MI condition than in the NP condition ($M = 1184$ms, 95% CI [1094, 1274]), $\chi^2(1)= 60.54$, $p< .001$, $[\Delta z]= .28$. The main effect of Sequence Type, $\chi^2<1$, and the two-way interaction, $\chi^2(2)= 1.97$, $p= .373$, were not significant.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)=327.03$, $p< .001$. Actual response times were significantly shorter in the PP condition ($M=$ 279ms, 95% CI [258, 300]) than in the MI condition ($M=$ 335ms, 95% CI [314, 356]), $\chi^2(1)=225.04$, $p< .001$, $[\Delta z]= .49$. The MI condition did not differ significantly from the NP condition, $\chi^2(1)= 2.89$, $p= .089$. The main effect of Sequence Type was also significant, $\chi^2(1)= 61.06$, $p< .001$, $[\Delta z]= .26$. Actual response times were significantly shorter for the close response sequences ($M=$ 301ms, 95% CI [280, 322]) than for the distant response sequences ($M=$ 331ms, 95% CI [310, 352]). The two-way interaction was not significant, $\chi^2(2)= 2.81$, $p= .245$.

Return Times.

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 770.82$, $p< .001$. Return times were significantly shorter in the PP condition ($M=$ 244ms, 95% CI [224, 265]) than in the MI condition ($M=$ 305ms, 95% CI [285, 326]), $\chi^2(1)= 563.93$, $p< .001$, $[\Delta z]= .67$. There was no significant difference between the MI and NP condition, $\chi^2(1)= 1.59$, $p= .208$. The effect of Sequence Type was also significant, $\chi^2(1)= 157.68$, $p< .01$, $[\Delta z]= .41$. Return times were shorter for the close response sequences ($M=$ 265ms, 95% CI [245, 286]) than for the distant response sequences ($M=$ 302ms, 95% CI [282, 323]). The two-way interaction was not significant, $\chi^2<1$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)=599.41$, $p< .001$. Return times were significantly shorter in the PP condition ($M=$ 246ms, 95% CI [223, 268]) than in the MI condition ($M=$ 298ms, 95% CI [275, 321]), $\chi^2(1)= 427.71$, $p< .001$, $[\Delta z]= .57$. The difference between the MI and NP condition ($M=$ 302ms, 95% CI [279, 326]) was not significant, $\chi^2(1)= 2.55$, $p= .110$, $[\Delta z]= .05$. The main effect of Sequence Type was significant, $\chi^2(1)= 264.83$, $p< .001$, $[\Delta z]= .45$. Return times were shorter for the close response sequences ($M=$ 260ms, 95% CI [236, 283]) than for the distant response sequences ($M=$ 301ms, 95% CI [278, 324]). The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2)= 1.07$, $p= .585$.

Error Rates. Error rates were analyzed by using a logistic mixed effects analysis wherein the binary response (correct/incorrect) was regressed on the fixed factors. Participants and the specific response sequences were again treated as crossed random effects.

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 239.56$, $p< .001$. Participants made less errors in the PP condition ($M= .02$, 95% CI [.01, .03]) than in the MI condition ($M= .04$, 95% CI [.03, .05]), $\chi^2(1)= 8.34$, $p< .01$, and less errors were made in the MI condition than in the NP condition ($M= .17$, 95% CI [.14, .21]), $\chi^2(1)= 128.90$, $p< .001$. The effect of Sequence Type and the two-way interaction were not significant, $\chi^2< 1$ and $\chi^2(2)= 2.16$, $p= .339$ respectively.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)= 267.55$, $p< .001$. Participants made less errors in the PP condition ($M= .03$, 95% CI [.01, .06]) than in the MI condition ($M= .06$, 95% CI [.03, .08]), $\chi^2(1)= 4.59$, $p< .05$, and less errors were made in the MI condition than in the NP condition ($M= .22$, 95% CI [.19, .24]), $\chi^2(1)= 228.92$, $p< .001$. The effect of Sequence Type was not significant, $\chi^2(1)= 1.94$, $p= .164$.

The two-way interaction between Training Condition and Response Sequence was significant, $\chi^2(2)= 6.57$, $p< .05$. In the MI condition, participants made less errors in the distant response sequences ($M= .04$, 95% CI [.01, .07]) than in the close response sequences ($M= .07$, 95% CI [.04, .10]), $\chi^2(1)= 4.85$, $p< .05$. In the NP condition, participants made less errors in the distant response sequences ($M= .20$, 95% CI [.17, .23]) than in the close response sequences ($M= .23$, 95% CI [.21, .26]), $\chi^2(1)= 5.19$, $p< .05$. This difference was not significant in the PP condition, $\chi^2(1) < 1$.

Discussion

We first consider the results of the training phase. Two findings are of importance. First, inter-home key intervals were longer in the MI condition than in the NP condition. Second, in the MI condition the effect of sequence distance was significant for the subsequent responses. Although participants did not physically enter the letters-keys, inter-home key intervals were thus shorter for close response sequences than for distant response sequences. These two findings suggest that participants did engage in a form of MI in the training phase, which incorporates parameters of physical properties, such as the distance between the home-key and the letter-keys.

Performance in the test phase was measured by using the inter home-key intervals, the actual response times, the return times and the error rates. All these dependent measures converge toward the same conclusions. Performance on the first response of the response sequence was better in the PP condition compared to the MI condition. In turn, performance in the MI condition was better compared to the NP condition. For the subsequent responses, performance was better in the PP condition compared to the MI and the NP condition. The latter two training conditions did not differ in terms of speed, albeit that the actual response times were marginally faster in the MI condition compared to the NP condition ($p = .089$). In addition, less errors were made in the MI condition compared to the NP condition. The overall pattern of results in the test phase thus suggests that while PP leads to improved response selection and movement execution, MI mainly leads to improved response selection. Before further speculating on the nature of the processes underlying the results of Experiment 1, we first sought the replicate these findings in a second experiment.

Experiment 2

A potential concern of Experiment 1 is that it was quite long and that each participant had to perform all three training conditions. The use of a within-subjects design could induce the carry-over of response strategies, which are known to modulate experimental results (e.g., Greenwald, 1976; Poulton, 1973, see Altmann, 2005 for a more recent example). Performance observed in the MI condition could be contaminated by strategies participants developed in the PP condition and vice versa. For instance, participants may have been inclined to actually enter letter-keys when the MI condition immediately followed the PP condition. An additional analysis, which included the counterbalancing order of the training conditions, did not suggest the presence of carry-over effects. However, the inclusion of this additional factor may have decreased the power to such an extent that a consistent pattern remained undetected. In Experiment 2 each participant performed only one of the three training conditions. Accordingly, the length of Experiment 2 was also reduced substantially, which could have an impact as such. Experiment 1 lasted for approximately 2 hours. Richardson (1967) pointed out that MI and motivation are strongly interrelated. The observation that MI only improved response selection could have been the result of participants becoming tired or demotivated during Experiment 1.

An additional concern about the procedure used in Experiment 1, relates to the participants' requirement to lift their response finger from the home-key in the training phase of the MI condition. Although participants did not physically enter a letter-key in this phase, it is conceivable that they performed small pointing movements toward the correct letter-keys. In order to minimize, the potential contribution of such movements, participants in Experiment 2 were instructed to only release pressure from the home-key, without actually lifting their finger from the home-key.

Taken together, Experiment 2 was identical to Experiment 1, for the exception that (a) a between-subjects design was now used; (b) each training condition (NP, MI, PP) was shortened so that participants would remain motivated during the course of the whole experiment; and (c) participants in the training phase of the MI condition were instructed to release the home-key without actually lifting their finger from the home-key. The question was whether we could replicate the results of Experiment 1.

Method

Participants and design. Sixty students at Ghent University participated for payment of 10 EURO. None of them participated in Experiment 1. The NP, PP, and MI conditions were now investigated in a between-subjects design. Twenty participants were randomly assigned to each training condition. In sum, a 3 (Training Condition: PP, MI, NP) by 2 (Phase: Training, Test) by 2 (Sequence Type: close, distant) mixed design was used with repeated measures on the last two factors.

Materials and procedure. The same materials and procedure were used as in Experiment 1, with four adjustments. First, participants either performed the NP, MI or PP condition. Second, within each training condition the number of blocks was reduced. Participants completed one practice run, followed by three experimental blocks, each consisting of five runs. Third, an additional familiarization phase consisting of five runs was added at the beginning of the experiment. In this phase, participants only executed the test phase such that participants became familiarized with the specific way of responding. Finally, participants in the training phase of the MI condition (and the NP condition) were instructed to release the home-key without lifting their finger from the home-key. In other words, they had to keep physical contact with the home-key at all time. During the course of the experiment this was closely monitored by the experimenter and participants were reminded of this instruction when necessary.

Results

Training phase. Data were pre-processed in the same way as in Experiment 1. This resulted in a data loss of 3% for the first response and 3% for the subsequent responses. Mean inter home-key intervals and corresponding standard deviations of each cell of the design are presented in Table 3.

First response. The main effect of Training Condition was significant, $\chi^2(2)=$ 166.80, $p< .001$. Inter-home key intervals were longer in the MI condition ($M=$ 1353ms, 95% CI [1258, 1448]) than in the NP condition ($M=$ 552ms, 95% CI [455, 649]), $\chi^2(1)=$ 1134.18, $p< .001$, $[\Delta z]=$ 1.55. There was no difference between the PP condition ($M=$ 1302ms, 95% CI [1207, 1397]) and the MI condition, $\chi^2< 1$. The main effect of Sequence Type was also significant, $\chi^2(1)=$ 9.73, $p< .01$, $[\Delta z]=$ .05. Inter-home key intervals were shorter for the close response sequences (M= 1061ms, 95% CI [1005, 1117]), than for the distant response sequences (M= 1086ms, 95% CI [1030, 1142]).

The interaction between Training Condition and Sequence Type was significant $\chi^2(2)$= 35.37, p< .001. Inter-home key intervals in the PP condition were shorter for the close response sequences (M= 1271ms, 95% CI [1176, 1367]) than for the distant response sequences (M= 1332ms, 95% CI [1237, 1428]), $\chi^2(1)$= 34.07, p< .001, [Δz]= .24. Inter-home key intervals in the MI condition were shorter for the close response sequences (M= 1342ms, 95% CI [1247, 1438]) than for the distant response sequences (M=1364ms, 95% CI [1269, 1460]), $\chi^2(1)$= 4.48, p< .05, [Δz]= .04. This difference was not significant in the NP condition, χ^2<1.

Subsequent responses. The main effect of Training Condition was significant, $\chi^2(2)$= 145.19, p< .001. Inter-home key intervals were shorter in the PP condition (M= 568ms, 95% CI [478, 659]) than in the MI condition (M=1131ms, 95% CI [1041, 1221]), $\chi^2(1)$= 75.09, p< .001, [Δz]= 1.36, and shorter in the NP condition (M= 371ms, 95% CI [279,464]) compared to the MI condition, $\chi^2(1)$= 133.63, p< .001, [Δz]= 1.83. The difference between the PP and NP condition was also significant, $\chi^2(1)$= 9.00, p< .01, [Δz]= .47. The main effect of Sequence Type was significant, $\chi^2(1)$= 43.32, p< .001, [Δz]= .10. Inter-home key intervals were shorter for the close response sequences (M= 677ms, 95% CI [624, 730]) than for the distant response sequences (M=715ms, 95% CI [662, 768]).

The interaction between Training Condition and Sequence Type was significant, $\chi^2(2)$= 109.92, p< .001. Inter-home key intervals in the PP condition were shorter for the close response sequences (M= 537ms, 95% CI [447, 628]), than for the distant response sequences (M=600ms, 95% CI [509, 690]), $\chi^2(1)$= 83.03, p< .001, [Δz]= .15. Inter-home key intervals in the MI condition were shorter for the close response sequences (M=1105ms, 95% CI [1015, 1195]), than for the distant response sequences (M=1157ms, 95% CI [1066-1247]), $\chi^2(1)$=57.18, p<.001, [Δz]= .13. This difference was not significant in the NP condition, χ^2<1.

Test phase. Errors were excluded from the analysis of the different timing components. This resulted in a data loss of 17%. Outlier trials were also excluded (3% for inter home-key interval, 3% for actual response times and 3% for return times). Means and corresponding standard deviations of each cell of the design are presented in Table 3. The additional analysis, only including the first trial of the test phase is presented in Appendix B and is again in line with main findings.

Inter Home-Key Intervals.

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 44.26$, $p< .001$. Inter-home key intervals were shorter in the PP condition ($M= 1370$ms, 95% CI [1260, 1480]) than in the MI condition ($M= 1564$ms, 95% CI [1453, 1674]), $\chi^2(1)= 5.96$, $p< .05$, $[\Delta z]= .31$, and shorter in the MI condition than in the NP condition ($M= 1903$ms, 95% CI [1789, 2017]), $\chi^2(1)= 17.52$, $p< .001$, $[\Delta z]= .54$. The main effect of Sequence Type was also significant, $\chi^2(1)= 6.08$, $p< .05$, $[\Delta z]= .10$. Inter-home key intervals were shorter for the close response sequences ($M= 1565$ms, 95% CI [1495, 1634]) than for the distant response sequences ($M= 1624$ms, 95% CI [1555, 1693]). The two-way interaction was not significant, $\chi^2(2)= 4.84$, $p= .089$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)= 30.59$, $p< .001$. Inter-home key intervals were shorter in the PP condition ($M= 617$ms, 95% CI [558, 676]) than in the MI condition ($M= 812$ms, 95% CI [752, 871]), $\chi^2(1)= 20.80$, $p< .001$, $[\Delta z]= .81$. The difference between the MI condition and the NP condition was not significant, $\chi^2< 1$. The main effect of Sequence Type was significant, $\chi^2(1)= 70.37$, $p< .001$, $[\Delta z]= .29$. Inter-home key intervals were shorter for the close response sequences ($M= 713$ms, 95% CI [678, 745]) than for the distant response sequences ($M= 783$ms, 95% CI [748, 819]). The two-way interaction was not significant, $\chi^2(2)= 2.62$, $p= .270$.

Actual Response Times.

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 44.31$, $p< .001$. Actual response times were significantly shorter in the MI condition ($M= 1172$ms, 95% CI [1078, 1268]) compared to the NP condition (M= 1511ms, 95% CI [1412, 1609]), $\chi^2(1)$= 23.43, p< .001, [Δz]= .59. There was no significant difference between the PP and MI condition, $\chi^2(1)$= 2.55, p= .110. There was no significant effect of Sequence Type, $\chi^2(1)$= 1.41, p= .236. The two-way interaction was not significant, $\chi^2(2)$= 4.31, p= .116.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)$= 29.47, p< .001. Actual response times were shorter in the PP condition (M= 320ms, 95% CI [287,353]) than in the MI condition (M= 417ms, 95% CI [384, 451]), $\chi^2(1)$= 16.77, p<.001, [Δz]= .67 The MI condition did not differ significantly from the NP condition, $\chi^2(1)$= 1.17, p= .279. The main effect of Sequence Type was also significant, $\chi^2(1)$= 26.92, p< .001, [Δz]= .19. Actual response times were faster for the close response sequences (M=375ms, 95% CI [355, 396]) than for the distant response sequences (M= 405ms, 95% CI [385, 425]).

The interaction between Training Condition and Sequence Type was significant, $\chi^2(2)$= 8.58, p< .05. Actual response times in the PP condition were shorter for the close response sequences (M= 297ms, 95% CI [262, 331]) than for the distant response sequences (M= 343ms, 95% CI [309, 377]), $\chi^2(1)$= 27.18, p< .001, [Δz]= .32. Actual response times in the MI condition were shorter for the close response sequences (M= 402ms, 95% CI [368, 436]) than for the distant response sequences (M= 433ms, 95% CI [399, 467]), $\chi^2(1)$= 12.11, p< .001, [Δz]= .21. This difference was not significant in the NP condition, χ^2<1.

Return Times.

First Response. The main effect of Training Condition was significant, $\chi^2(2)$= 21.94, p< .001. Return times were shorter in the PP condition (M= 294ms, 95% CI [263, 326]) than in the MI condition (M= 387ms, 95% CI [356, 418]), $\chi^2(1)$= 16.75, p< .001, [Δz]= .83. There was no significant difference between the MI and NP condition, χ^2< 1. The main effect of Sequence Type was also significant, $\chi^2(1)$= 85.70, p< .001, [Δz]= .31. Return times were shorter for the close response sequences (M= 337ms, 95% CI [317, 355]) than for the distant response sequences (M= 371ms, 95% CI [352, 390]).

The interaction between Training Condition and Sequence Type was significant,

$\chi^2(2)= 6.72$, $p< .05$. The effect of Sequence Type was large in the PP (close response sequences: $M= 276$ms, 95% CI [244, 308]; distant response sequences: $M= 312$ms, 95% CI [280, 344], $\chi^2(1)= 39.56$, $p<.001$, $[\Delta z]= .32$) and the NP condition (close response sequences: $M=364$ms, 95% CI [331, 397]; distant response sequences: $M= 408$ms, 95% CI [375, 441], $\chi^2(1)= 49.37$, $p<. 001$, $[\Delta z]= .39$). The effect of Sequence Type was smaller, albeit still significant, in the MI condition (close response sequences: $M= 375$ms, 95% CI [343, 407]; distant response sequences: $M= 399$ms, 95% CI [367, 430], $\chi^2(1)= 16.08$, $p<.05$, $[\Delta z]= .21$).

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)= 23.07$, $p< .001$. Return times were shorter in the PP condition ($M= 296$ms, 95% CI [266-326]) than in the MI condition ($M= 389$ms, 95% CI [359, 419]), $\chi^2(1)= 18.57$, $p<.001$, $[\Delta z]= .87$. The difference between the MI and NP condition was not significant, $\chi^2< 1$. The main effect of Sequence Type was also significant, $\chi^2(1)= 156.88$, $p< .001$, $[\Delta z]= .38$. Return times were shorter for the close response sequences ($M= 333$ms, 95% CI [316, 351]) than for the distant response sequences ($M= 374$ms, 95% CI [356, 392]). The two-way interaction was not significant, $\chi^2(2)= 4.08$, $p= .130$.

Error Rates.

First Response. The effect of Training Condition was significant, $\chi^2(2)= 16.48$, $p<.001$. Participants made more errors in the NP condition ($M= .17$, 95% CI [.14, .21]) compared to the MI condition ($M= .10$, 95% CI [.08, .13]), $\chi^2(1)= 9.27$, $p< .01$. There was no difference between the MI and PP condition ($M=.09$, 95% CI [.06, .11), $\chi^2(1)< 1$. The effect of Sequence Type and the interaction between Training Condition and Sequence Type were not significant, $\chi^2<1$.

Subsequent Responses. The effect of Training Condition was significant, $\chi^2(2)= 37.09$, p< .001. Participants made less errors in the MI condition ($M=.12$, 95% CI [.08, .15]), compared to the NP condition ($M= .21$, 95% CI [.18, .24]), $\chi^2(1)= 15.50$, $p<.001$. There was no difference between the PP condition ($M=.07$, 95% CI [.04, .11]) and MI condition, $\chi^2(1)= 3.36$, $p= .067$. The effect of Sequence Type and the interaction between Training

Condition and Sequence Type were both not significant, $\chi^2(1)$=1.41, p=.234 and $\chi^2(2)$= 2.37, p=.306, respectively.

Discussion

The results of Experiment 2 are in line with the results of Experiment 1. In the training phase, the inter-home key intervals were again longer in the MI condition compared to the NP condition and the sequence distance modulated the length of inter-home key intervals in the MI condition. In contrast to Experiment 1, the effect of the sequence distance was not only present on the first response but also on the subsequent responses. These results provide even more clear evidence that participants engaged in MI as was intended by our procedure. In contrast to Experiment 1, the inter-home key intervals did not differ significantly between the first response of the PP and the first response of the MI condition.

In the test phase, inter-home key intervals and return times were shorter in the PP condition compared to the MI condition. However, actual response times and error rates did not differ significantly between the MI and PP condition. On the subsequent responses, we mainly observed performance improvement after PP. In line with Experiment 1, we only observed a significant difference between the MI and NP condition for the error rates. Error rates did not differ between the MI and PP condition. Taken together, the results of Experiment 2 converge with the findings of Experiment 1 and this even though: (a) a between-subjects design was used; (b) the experiment was drastically shortened; and (c) more stringent control was applied with respect to the release of the home-key in the training phase of the MI condition. We further consider these results in the General Discussion.

General Discussion

The present study investigated the effect of MI on the application of newly instructed S-R mappings. The results of two experiments suggest that MI improves performance, albeit to a lesser extent than PP. In addition, PP improves the selection and retrieval of a response sequence, as well as the execution of the movements corresponding with this response sequence. In contrast, MI mainly improves response selection but does not seem to strongly influence movement execution. We consider both findings in more detail.

Motor Imagery and Learning via Instructions

Previous research on the effect of PP on the application of novel instructions, suggested that PP leads to a quick shift in processing mode. Initial performance is supposedly based on an abstract representation, which is formed on the basis of instructions (Ruge & Wolfensteller, 2010, see also Liefooghe et al., 2012; Meiran et al., 2012) or a slow processing route, which implements S-R associations on the basis of instructions (Ramamoorthy & Verguts, 2012). PP elicits the creation of a pragmatic task representation (Ruge & Wolfensteller, 2010) or a fast processing route (Ramamoorthy & Verguts, 2012), which takes over control and leads to more automatic behavior. It can be hypothesized that performance in the NP condition was based mainly on an abstract representation or a slow route, which led to a particularly slow and error-prone performance. In line with the proposals of Ruge and Wolfensteller (2010), the improvement in performance induced by PP suggests that a pragmatic representation was formed on the basis of PP, which quickly took over control. This pragmatic representation is supposed to be more fine-grained than the initial representation and includes various parameters that drive the skilled execution of a task.

Within the framework of Ruge and Wolfensteller (2010), the impact of MI can be interpreted in two ways. First, MI also leads to the formation of a pragmatic task representation. The current observation that the effect of MI was less beneficial than the effect of PP, suggests that the representation formed on the basis of MI includes less task parameters needed to attain skilled performance. Such parameters may only become represented on the basis of overt task execution. An essential aspect of overt execution is that it triggers perceivable effects in the environment (i.e., action effects). These action effects can take different forms. For instance, entering the letter-keys in the training phase of the PP condition, immediately resulted in the appearance of the corresponding letters.

Within theories of action-effect learning (e.g., Elsner & Hommel, 2001; Hommel, 2009), it is reasonable to assume that entering a letter-key and perceiving the corresponding letter during training led to the formation of a response-effect contingency, which facilitated performance in the subsequent test phase. In contrast, during the training phase of the MI condition, the letters appeared when participants pressed the home-key after having performed an imagined movement. The action-effects in the MI condition were thus delayed and contingent upon a different overt response. Response-effect contingencies between the imagined responses and corresponding letters may thus not have been formed under these conditions and thus not incorporated in the task representation. Such scenario does not only apply for the appearance of letters during the training phase, but for each type of sensory-motor experience the overt execution of a response induces, which is not induced by the covert execution of a response (e.g., Lotze & Halsband, 2006; Mulder, Zijlstra, Zijlstra, Hochstenbach, 2004; Rieger, 2012). PP may thus lead to a more detailed pragmatic task representation through the integration of response-effect contingencies on the basis of action-effects, which only follow upon overt response execution. A related difference concerns the error feedback experienced during the training phase. Such feedback was present in the PP condition, but was absent in the MI condition. Rieger et al. (2011) demonstrated that the experience of error feedback constitutes an important difference between PP and MI. In addition, simulating errors during MI, enhanced the beneficial effect of MI. The operation of error feedback can also be considered in terms of action-effect learning and the study of Reiger et al. (2011) suggests that enriching MI with the simulation of the different action-effects an overt response execution can be associated with, may lead to more finegrained task representations during MI and thus reduce the difference between PP and MI.

It could also be argued that the beneficial effect of MI may increase when providing participants with longer training phases. Within the model of Ramamoorthy and Verguts (2012), the fast route gradually learns new contingencies on the basis of the Hebbian learning of associations between stimulus and response codes. Such Hebbian learning follows the application of the new S-R mappings through the slow route. It is reasonable to assume that the application of new S-R mappings in the training phase of the MI condition offers a less strong input for the fast route compared to the application of new S-R mappings in the training phase of the PP condition. Accordingly, the degree by which the fast route takes over control may depend on the extent by which the S-R mappings are applied on the basis of the slow route. Taken together, the different effects of MI and PP are thus confined to the experimental parameters that were used in the present study and we cannot exclude that using different parameters could decrease and even eliminate the difference between MI and PP.

A second interpretation of the present results is that MI does not lead to the formation of a pragmatic task representation. In such view, the beneficial effect of MI is not related to a shift in processing mode, but to an enhancement of the processes involved in the maintenance and application of the initial representation that is formed on the basis of instructions. Although we cannot exclude such account on the basis of the present results, the many existing demonstrations that MI can lead to long-term performance improvement (e.g., Clark, 1960; Jarus & Ratzon, 2000; McBride & Rothstein, 1979; Wohldmann et al., 2007, 2008), challenge the idea that MI would not result in the formation of long-term representations. In addition, during the training phase of the MI and PP conditions it was possible to build additional associations, possibly through verbal rehearsal, between stimuli and response-key labels during the training phase, because the letters of the response sequence appeared on the screen after pressing the respective key (PP) or the home-key (MI).

The present results are in line with the conclusion of Driskell et al. (1994; see also Feltz & Landers, 1983) that MI has a sizable effect, which is nevertheless smaller than the effect of PP. This contrasts with previous studies reporting the absence of beneficial effects of MI (e.g., Corbin, 1967; Shanks & Cameron 2000; Shick, 1970; Smyth, 1975). Although differences between the task used in the present study and the tasks used in previous studies may account for these diverging results, it is also important to note that the present study used a stringent procedure in which participants were not only instructed to perform imagined movements but were also deceived with a cover story, which created the impression that we could actually measure the amount of effort participants put into MI. In addition, the training phase in the MI condition and the test phase were highly similar. Based on the transfer-appropriate processing theory of Kolers and Roediger (1984), Shanks and Cameron (2000) suggested that increasing the similarity between training and test phases optimizes the transfer of learning and thus increases the probability to observe effects of MI. However, it could be argued that the procedure we used induced participants in the training phase of the MI condition to partly initiate overt typing movements. Although Experiment 2 controlled for finger-pointing movements, we cannot rule out the contribution of other type of responses such as motor activation, eye movements toward the letter-keys, etc... and future research will be needed to investigate their impact.

Response Selection and Movement Execution

The results of both experiments indicate that MI mainly modulated processes related to response selection and did not strongly influence processes related to movement execution. Our results are thus at odds with the observation of Wohldmann et al. (2007, 2008) that MI decreases the movement time but not the reaction time, which even increased in some of their experiments. Wohldmann et al. (2007) suggested that reaction times may have been inflated by chunking strategies. More precisely, during practice participants learn to encode the strings of digits in the digit data-entry task as chunks, which supposedly led to an increase of the reaction time and a decrease of the movement time. In the present study, arbitrary S-R mappings were used, which related a picture of an object or animal to a particular sequence of letters. Chunking at the level of stimulus encoding was thus not possible. Our results, furthermore, suggest that the instructed response sequences were immediately grouped and retrieved as a whole prior to the first response. In the test phase of the NP condition, the first response was strikingly slower than the subsequent responses. For instance, the mean inter-home key interval for the first response was 1496ms in Experiment 1 and 1903ms in Experiment 2. In contrast, the mean inter-home key interval for the subsequent responses was 646ms in Experiment 1 and 832ms in Experiment 2.

Conclusions

The results of two experiments indicate that MI leads to a sizable improvement of the application of novel instructions by enhancing response selection, but not so much by enhancing movement execution. We propose that MI can result in a quick shift in processing mode through the creation of a pragmatic task representation, albeit a less detailed one compared to the representation created on the basis of PP. We do, however, not exclude that enriching the MI experience with additional forms of simulation, may eliminate or reduce the difference between MI and PP.

As mentioned in the Introduction, research on learning via instructions converges towards the hypothesis that verbal instructions can be implemented into a procedural representation, which triggers automatic effects on behavior (e.g., Liefooghe et al., 2012; Meiran et al., 2012, 2015). In view of the beneficial effects of MI, future research may want to focus on the role of MI in the construction of a procedural representation on the basis of instructions. Whereas in the current study MI was imposed to the participants, it is reasonable to assume that encoding and implementing novel instructions is driven by a more spontaneous form of MI through which novel instructions are simulated prior to their actual application (Ruge & Wolfensteller, 2010).

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Tables

Table 1. Overview of the Dutch word stimuli.

aap	broek	gieter	kip	pauw	taart	zadel
ananas	brood	gitaar	koe	peer	tafel	zak
anker	brug	glas	kok	pet	tak	zebra
appel	bureau	haai	kom	piano	tand	zon
arm	bus	haak	konijn	pijl	tank	zwaan
asbak	cactus	haar	koning	pijp	tent	zweep
auto	clown	hak	kooi	pincet	tijger	
baard	cowboy	hamer	kraan	puzzel	tol	
baby	dak	hand	kreeft	racket	tomaat	
bad	das	harp	kroon	radijs	ton	
bal	deur	hart	kruis	radio	touw	
ballon	dokter	heks	kussen	regen	trap	
banaan	doos	helm	ladder	ring	trein	
bank	douche	hert	lama	robot	Uil	
bed	draak	hoed	leeuw	rugzak	vaas	
been	duif	hoef	lepel	schaap	varken	
beer	duim	hond	maan	schaar	vinger	
beker	duivel	huis	mais	schelp	Vis	
berg	eend	iglo	mand	schoen	vlag	
bijl	eikel	jas	masker	sigaar	vlieg	
blad	emmer	jojo	meisje	sjaal	vlot	
blik	eskimo	kaars	mes	slak	voet	
bloem	ezel	kaas	mixer	slang	vork	
boek	fiets	kam	muis	slee	vos	
bom	fles	kameel	muur	spin	vuur	

boom	gebit	kanon	neus	spook	wiel
boot	geest	kast	oog	ster	wolk
bord	geit	kerk	oor	stoel	worst
brief	geweer	kers	paard	strik	wortel
bril	gewei	kikker	pan	stuur	zaag

Table 2. Cell means and corresponding standard deviations of Experiment 1. Standard deviations are printed between brackets. Timing components are expressed in milliseconds.

		first response		subsequent responses	
		close	distant	close	distant
Training Phase					
Inter home-key interval	PP	1214 (364)	1243 (331)	518 (167)	579 (175)
	MI	995 (467)	986 (454)	668 (328)	689 (355)
	NP	389 (271)	383 (260)	294 (143)	293 (142)
Test Phase					
Inter home-key interval	PP	1067 (272)	1083 (243)	493 (142)	564 (146)
	MI	1328 (516)	1395 (557)	598 (194)	678 (200)
	NP	1474 (707)	1530 (766)	618 (210)	681 (184)
Actual response times	PP	838 (254)	815 (217)	264 (103)	296 (107)
	MI	1038 (455)	1055 (461)	319 (112)	352 (103)
	NP	1175 (664)	1201 (717)	332 (122)	354 (101)
Return times	PP	226 (54)	263 (56)	226 (53)	266 (55)
	MI	286 (95)	325 (99)	277 (93)	321 (105)
	NP	291 (96)	329 (93)	284 (105)	324 (97)
Error rates	PP	0.02 (0.14)	0.02 (0.15)	0.03 (0.16)	0.04 (0.19)
	MI	0.05 (0.22)	0.03 (0.18)	0.07 (0.26)	0.04 (0.19)
	NP	0.18 (0.39)	0.19 (0.39)	0.23 (0.42)	0.20 (0.40)

Table 3. Cell means and corresponding standard deviations of Experiment 2. Standard deviations are printed between brackets. Timing components are expressed in milliseconds.

		first response		subsequent responses	
		close	distant	close	distant
Training Phase					
Inter home-key interval	PP	1280 (354)	1328 (341)	541 (119)	603 (111)
	MI	1342 (474)	1358 (481)	1104 (370)	1152 (388)
	NP	554 (230)	548 (234)	375 (221)	374 (221)
Test Phase					
Inter home-key interval	PP	1333 (547)	1403 (595)	573 (193)	661 (226)
	MI	1568 (540)	1570 (500)	785 (221)	848 (214)
	NP	1828 (629)	1961 (751)	800 (225)	864 (220)
Actual response times	PP	1052 (496)	1072 (496)	297 (123)	343 (138)
	MI	1186 (477)	1167 (436)	404 (126)	436 (127)
	NP	1453 (593)	1544 (707)	437 (166)	448 (137)
Return times	PP	276 (79)	312 (99)	274 (76)	318 (95)
	MI	377 (109)	401 (104)	374 (107)	408 (98)
	NP	367 (104)	413 (116)	362 (91)	412 (102)
Error rates	PP	0.10 (0.30)	0.08 (0.28)	0.09 (0.28)	0.06 (0.24)
	MI	0.10 (0.31)	0.11 (0.31)	0.11 (0.32)	0.12 (0.33)
	NP	0.18 (0.39)	0.17 (0.38)	0.22 (0.41)	0.20 (0.40)

Figure Captions

Figure 1. (a) Schematic representation of the response key-board. Letters in the green area were used for the distant response sequences. Letters in the red area were used for the close response sequences. (b) Example of the stimulus display during the test phases and training phases of the PP and MI condition. (c) Example of the stimulus display during the test phases and training phases of the NP condition.

Figure 2. Outline of the procedure.

Figure 3. Overview of the timing components that were measured.

Figure 4. Overview of the effect of Training Condition in the Test Phase of Experiment 1. Error bars represent the 95% CI.

Figure 5. Overview of the effect of Training Condition in the Test Phase of Experiment 2. Error bars represent the 95% CI.

Figures

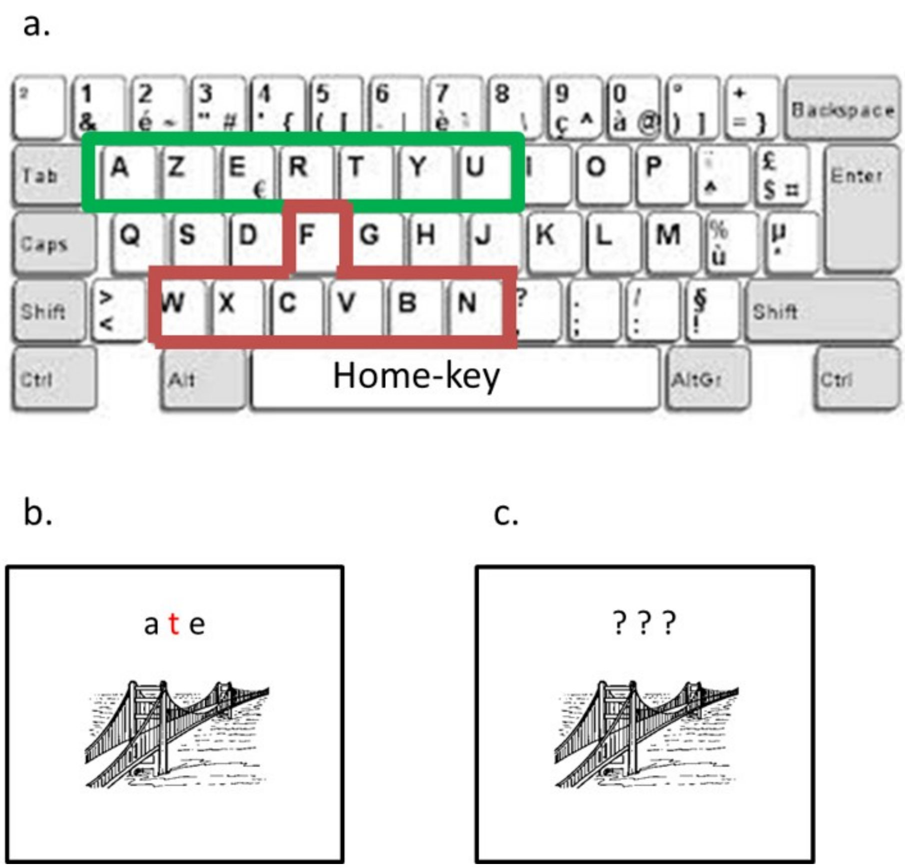

Figure 1

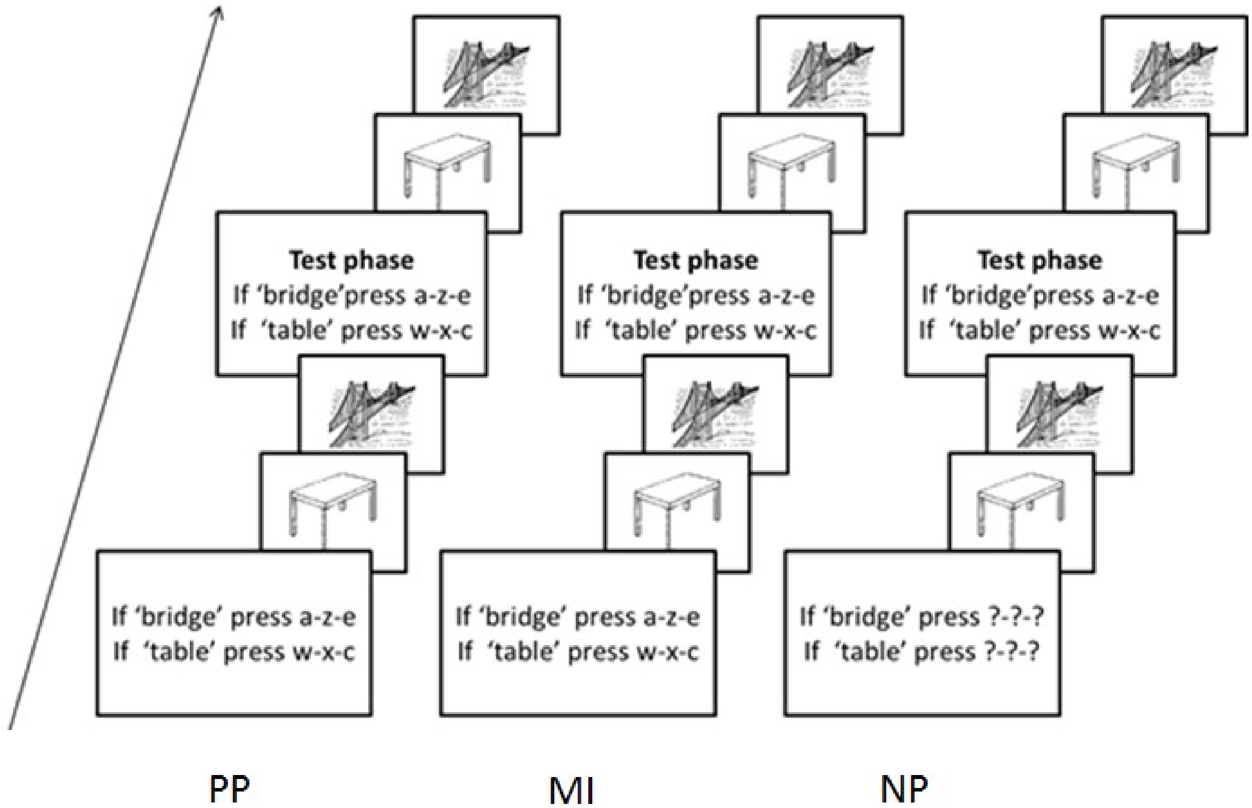
Test phase
If 'bridge'press a-z-e
If 'table' press w-x-c
Test phase
If 'bridge'press a-z-e
If 'table' press w-x-c
Test phase
If 'bridge'press a-z-e
If 'table' press w-x-c
If 'bridge' press a-z-e
If 'table' press w-x-c
If 'bridge' press a-z-e
If 'table' press w-x-c
If 'bridge' press ?-?-?
If 'table' press ?-?-?
PP
MI
NP

Figure 2

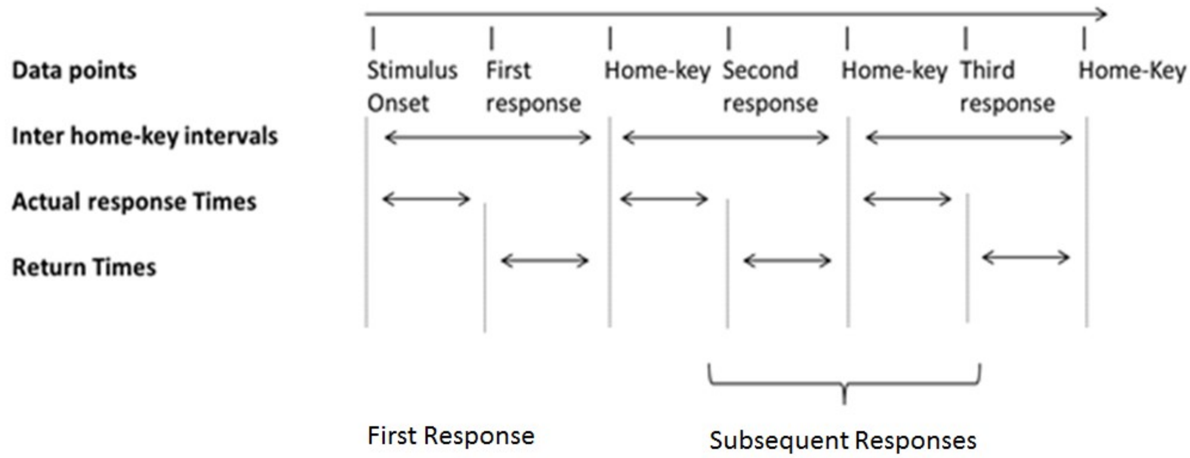
Data points
Stimulus Onset
First response
Home-key
Second response
Home-key
Third response
Home-Key
Inter home-key intervals
Actual response Times
Return Times
First Response
Subsequent Responses

Figure 3

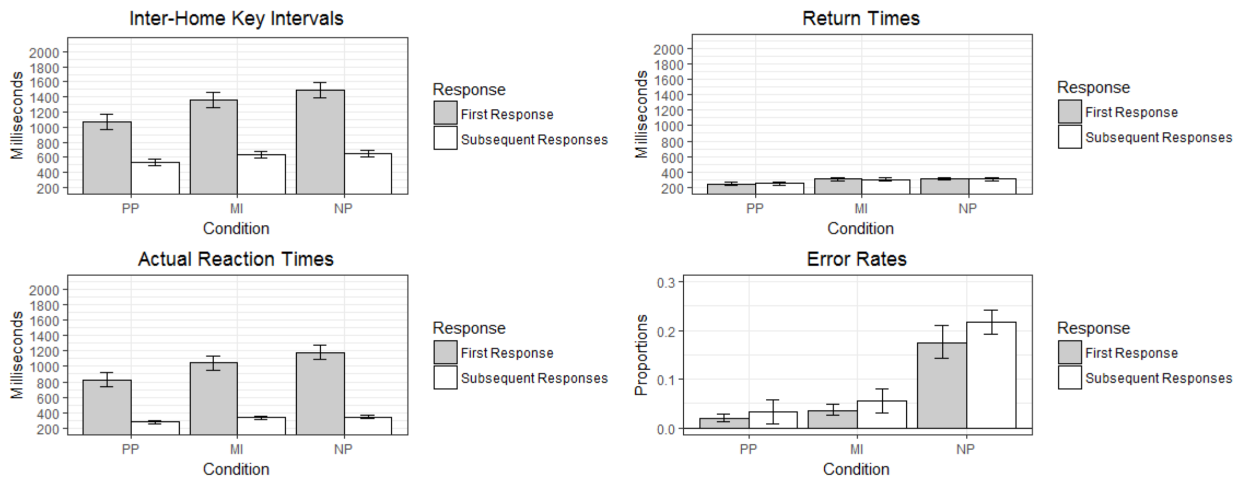
Inter-Home Key Intervals
Milliseconds
Condition
PP
MI
NP
Response
First Response
Subsequent Responses
Return Times
Actual Reaction Times
Error Rates
Proportions

Figure 4

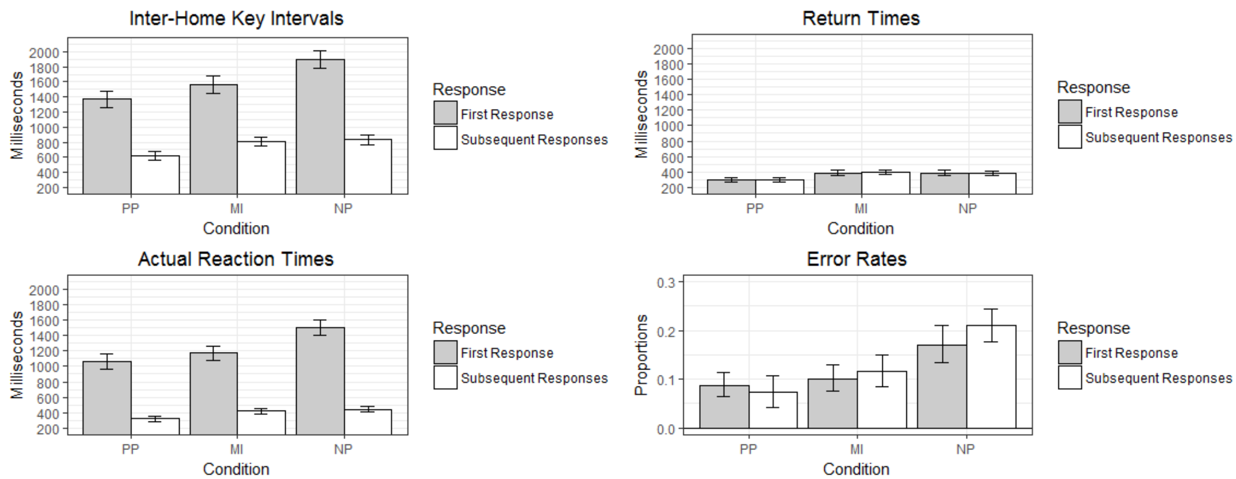
Inter-Home Key Intervals
Milliseconds
Condition
PP
MI
NP
Response
First Response
Subsequent Responses
Return Times
Actual Reaction Times
Error Rates
Proportions

Figure 5

Appendix A

Inter Home-Key Intervals

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 85.99$, $p<$ .001. The length of the inter-home key intervals was significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 36.53$, $p< .001$, and significantly shorter in the MI condition than in the NP condition, $\chi^2(1)= 10.95$, $p< .001$. Neither the main effect of Sequence Type, $\chi^2(1)< 1$, not the two-way interaction were significant, $\chi^2(2)< 1$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)=$ 30.46, $p< .001$. Inter-home key intervals were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 21.84$, $p< .001$. The MI condition and the NP condition did not differ significantly, $\chi^2(1)< 1$. The effect of Sequence Type was also significant, $\chi^2(1)= 7.76$, $p< .01$. Inter-home key intervals were shorter for the close response sequences than for the distant response sequences. The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2)< 1$.

Actual Response Times

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 88.27$, $p<$ .001. Actual response times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 34.33$, $p< .001$. Actual response times were significantly shorter in the MI condition than in the NP condition, $\chi^2(1)= 13.48$, $p< .001$. The main effect of Sequence Type and the two-way interaction were not significant, χ^2s<1.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)=$ 30.36, $p< .001$. Actual response times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 225.04$, $p< .001$. The MI condition did not differ significantly from the NP condition, $\chi^2(1)= 2.89$, $p= .089$. The main effect of Sequence Type was also significant, $\chi^2(1)= 5.29$, $p< .05$. Actual response times were significantly shorter for the close response sequences than for the distant response sequences. The two-way interaction was not significant, $\chi^2(2) < 1$.

Return Times

First Response. The main effect of Training Condition was significant, $\chi^2(2) = 49.74$, $p < .001$. Return times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1) = 34.01$, $p < .001$. There was no significant difference between the MI and NP condition, $\chi^2(1) < 1$. The effect of Sequence Type was also significant, $\chi^2(1) = 11.97$, $p < .001$. Return times were shorter for the close response sequences than for the distant response sequences. The two-way interaction was not significant, $\chi^2 < 1$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2) = 34.48$, $p < .001$. Return times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1) = 22.34$, $p < .001$. The difference between the MI and NP condition was not significant, $\chi^2(1) < 1$. The main effect of Sequence Type was significant, $\chi^2(1) = 13.58$, $p < .001$. Return times were shorter for the close response sequences than for the distant response sequences. The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2) < 1$.

Error Rates

First Response. The main effect of Training Condition was significant, $\chi^2(2) = 24.35$, $p < .001$. Participants made less errors in the MI condition than in the NP condition, $\chi^2(1) = 15.06$, $p < .001$. The MI and the PP condition did not differ significantly, $\chi^2(1) < 1$. The effect of Sequence Type and the two-way interaction were not significant, χ^2s < 1.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2) = 31.94$, $p < .001$. Participants made less errors in the MI condition than in the NP condition, $\chi^2(1) = 23.11$, $p < .001$. The MI and the PP condition did not differ significantly, $\chi^2(1) < 1$. The main effect of Sequence Type and the two-way interaction were not significant, χ^2s < 1.

Appendix B

Inter Home-Key Intervals

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 27.99$, $p<$ .001. The length of the inter-home key intervals was marginally shorter in the PP condition than in the MI condition, $\chi^2(1)= 3.39$, $p=$ .066, and significantly shorter in the MI condition than in the NP condition, $\chi^2(1)= 11.93$, $p<$ .001. Neither the main effect of Sequence Type, $\chi^2(1)< 1$, not the two-way interaction were significant, $\chi^2(2)< 1$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)=$ 26.45, $p<$ .001. Inter-home key intervals were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 18.75$, $p<$ .001. The MI condition and the NP condition did not differ significantly, $\chi^2(1)< 1$. The effect of Sequence Type was also significant, $\chi^2(1)= 4.56$, $p<$ .05. Inter-home key intervals were shorter for the close response sequences than for the distant response sequences. The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2)< 1$.

Actual Response Times

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 31.72$, $p<$ .001. Actual response times were significantly shorter in the MI condition than in the NP condition, $\chi^2(1)= 17.64$, $p<$ .001. Actual response times did not differ between the PP and the MI condition, $\chi^2(1)= 1.58$, $p=$ .208. Neither the main effect of Sequence Type, nor the two-way interaction were significant, χ^2s< 1.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)=$ 23.64, $p<$ .001. Actual response times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 13.84$, $p<$ .001. The MI condition did not differ significantly from the NP condition, $\chi^2(1)< 1$. The main effect of Sequence Type and the two-way interaction were not significant, $\chi^2(1)= 2.16$, $p=$ .141 and $\chi^2(2)= 1.24$, $p=$ .537 respectively.

Return Times

First Response. The main effect of Training Condition was significant, $\chi^2(2)= 22.82$, $p< .001$. Return times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 17.95$, $p< .001$. There was no significant difference between the MI and NP condition, $\chi^2(1)< 1$. The effect of Sequence Type was also significant, $\chi^2(1)= 5.76$, $p< .001$. Return times were shorter for the close response sequences than for the distant response sequences. The two-way interaction was not significant, $\chi^2(2)= 1.52$, $p= .469$.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)= 28.09$, $p< .001$. Return times were significantly shorter in the PP condition than in the MI condition, $\chi^2(1)= 22.46$, $p< .001$. The difference between the MI and NP condition was not significant, $\chi^2(1)< 1$. The main effect of Sequence Type was significant, $\chi^2(1)= 7.87$, $p< .01$. Return times were shorter for the close response sequences than for the distant response sequences. The interaction between Training Condition and Sequence Type was not significant, $\chi^2(2)< 1$.

Error Rates

First Response. The main effect of Training Condition was marginally significant, $\chi^2(2)= 5.53$, $p= .063$. Participants made marginally less errors in the MI condition than in the NP condition, $\chi^2(1)= 3.25$, $p= .072$. The MI and the PP condition did not differ significantly, $\chi^2(1)< 1$. The effect of Sequence Type and the two-way interaction were not significant, χ^2s< 1.

Subsequent Responses. The main effect of Training Condition was significant, $\chi^2(2)= 7.79$, $p< .05$. Participants made less errors in the MI condition than in the NP condition, $\chi^2(1)= 3.12$, $p= .077$. The MI and the PP condition did not differ significantly, $\chi^2(1)= 1.03$, $p= .077$. The main effect of Sequence Type and the two-way interaction were not significant, χ^2s<1.