KU LEUVEN

GROEP BIOMEDISCHE WETENSCHAPPEN

FACULTEIT BEWEGINGS- EN REVALIDATIEWETENSCHAPPEN

The effect of repeating stimuli on training and on performance assessment

door Lore Vleugels

masterproef aangeboden tot het behalen van de graad van Master of Science in de lichamelijke opvoeding en de bewegingswetenschappen

o.l.v.

dr. R. Hardwick, promotor

prof. dr. S. Swinnen, co-promotor

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"Niet in het snijden van de padie ligt de vreugde, de vreugde is in het snijden van de padie die men zelf heeft geplant"

Multatulli

WOORD VOORAF

Graag wil ik starten met enkele woorden van dank. In de eerste plaats wil ik mijn dank betuigen aan mijn promotor, dr. Robert Hardwick, voor zijn uitstekende begeleiding tijdens deze masterproef en zijn onvoorwaardelijke steun en begrip op momenten dat het moeilijk ging. Hij gaf me de kans om tijd te spenderen met mijn familie wanneer mijn Bompa overleed in oktober 2018. Bovendien inspireerde dr. Robert Hardwick mij telkens weer met zijn opbouwende feedback en zijn uitstekende wetenschappelijke kennis waardoor ik gaandeweg groeide in dit project.

Ik wil ook graag alle jongvolwassenen bedanken die hebben deelgenomen aan de studie. Zonder hun medewerking was de totstandkoming van deze masterproef niet mogelijk geweest. Ook dank ik de faculteit voor het gebruik van het materiaal en het labo om testen uit te voeren.

Woorden van dank gaan uiteraard ook uit naar mijn ouders, voor de prachtige kansen en opportuniteiten die ik heb gekregen gedurende mijn jaren als student. Zowel op emotioneel als financieel vlak stonden ze steeds voor mij klaar. Zonder hen had ik absoluut niet gestaan waar ik nu sta. Ook mijn twee broers, Toon en Robbe, wil ik danken voor hun pertinente begrip en steun. Graag wil ik ook mijn grootouders en meter in het bijzonder bedanken. De lieve en steunende berichtjes die me telkens weer moed gaven om door te gaan, het steeds weer opnieuw branden van kaarsjes voor een goede afloop. In dit dankwoord mag zeker mijn Bompa niet ontbreken. In de jaren die voorafgingen aan mijn universitaire studies leerde hij me kritisch zijn tegenover mezelf en dat heeft beslist zijn vruchten afgeworpen in de loop van de voorbije jaren. Ook mijn Opa kan beslist niet ontbreken in deze dankbetuiging. Ik ben enorm trots dat ik de derde generatie op rij ben die aan het sportkot studeert. Ik ben ervan overtuigd dat hij bijzonder fier zou zijn geweest indien hij dit nog had kunnen meemaken. Hoewel zowel Bompa als Opa reeds zijn heengegaan, wil ik hen bedanken voor wat ze me op welke manier dan ook hebben meegegeven.

Borgerhout, 12 mei 2019 L.V.

SITUERING

Deze masterproef kadert binnen het Laboratorium Motorische Controle van de onderzoeksgroep Bewegingscontrole en Neuroplasticiteit onder leiding van Prof. Dr. Stephan Swinnen. Deze onderzoeksgroep behoort tot de Faculteit Bewegings- en Revalidatiewetenschappen aan de KU Leuven. Meer specifiek stond deze masterproef onder het toezicht van dr. Robert Hardwick, promotor, en Prof. Dr. Stephan Swinnen, co-promotor. Dr. Hardwick zijn voornaamste onderzoeken bestuderen hoe mensen bewegingen controleren en vaardigheden leren. Deze studies includeren zowel louter gedragsstudies als studies waarbij men gebruikmaakt van non-invasieve hersenstimulatie en neuroimaging. Een van zijn grootste interesses omvat hoe mensen bewegingen aanleren en hoe we deze uiteindelijk automatiseren na extensieve oefening (Hardwick et al. 2018). Daarnaast bestudeert hij de nadelige effecten van het ouder worden en van een beroerte op de bewegingscontrole (Hardwick en Celnik 2017; Hardwick et al. 2017). Tot slot voert hij onderzoek naar hoe het observeren van acties een impact heeft op het motorisch systeem (Loporto et al. 2011; Hardwick en Edwards 2011).

In de sport trachten we steeds het beste te bereiken, na een blessure of beroerte proberen we zo snel mogelijk terug optimaal te functioneren, als kind leren we allerlei vaardigheden, etc. Al deze zaken hebben één ding gemeenschappelijk, namelijk het leren (of verbeteren) van een vaardigheid of skill. Nu is de vraag: “Wat is de optimale leermethode?” Reeds vele jaren heeft men onderzocht hoe men het proces van leren en trainen kan optimaliseren. Verschillende methodes werden hierbij onderzocht: zowel op het gedrags- (random versus geblokte oefening, leren met of zonder feedback, expliciet versus impliciet leren) (Magill en Anderson 2013) als het neurale niveau (Reis et al. 2009; Galea et al. 2011; Hardwick en Celnik 2014; maar zie ook Vallence et al. 2013; Lopez-Alonso et al. 2015; Lopez-Alonso et al. 2018).

Tegen het einde van de 21ste eeuw focuste men zich in vele onderzoeken op de gevolgen van herhaling tijdens het uitvoeren van een motorische taak (Fecteau en Munoz 2003; Gupta en Cohen 2002). “Repetitie priming” is een impliciet geheugenfenomeen (Gupta en Cohen 2002) en verwijst naar het faciliteren in het verwerken van een stimulus als resultaat van eerdere blootstelling aan deze stimulus (Schwartz en Hashtroudi 1991). Meer recente studies onderzochten het effect van geblokte versus gerandomiseerde oefening. Hier verwijst geblokte oefening naar het oefenen met herhaling op het niveau van de blokken, terwijl gerandomiseerde oefening verwijst naar contextuele interferentie op het niveau van de blokken (i.e. oefenen van blokken van verschillende taken in een random volgorde). De term “contextuele interferentie” wordt gebruikt om te verwijzen naar het oefenen van verschillende taken of skills tijdens training wat leidt tot voordelige effecten wat betreft het leren (Magill en Anderson 2013). Hoewel studies voornamelijk het wisselen tussen taken bestudeerden op het blokniveau, werd het onderzoeken van het wisselen op het individuele trialniveau, tot zover onze kennis reikt, nog niet vaak onderzocht. Bijgevolg tracht de huidige masterproef deze vraag te beantwoorden. We onderzochten het effect van verandering of herhaling van opeenvolgende trials tijdens de oefenperiode op de prestatie. Bovendien maakten we gebruik van een speed-accuracy trade-off als maat om de prestatie te beoordelen aangezien deze een accurater resultaat geeft dan meetmethoden die eerder werden gehanteerd (Reis et al. 2009; Shmuelof et al. 2012). Het doel van de huidige studie is om te onderzoeken hoe we het leren van een vaardigheid kunnen verbeteren door het manipuleren van de taakuitvoering op het eenvoudige gedragsniveau. Dit is van maatschappelijk belang omdat resultaten van dit onderzoek kunnen leiden tot vooruitgang in verscheidene domeinen buiten de onderzoekswereld zoals bijvoorbeeld sport, muziek en rehabilitatie.

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The effect of repeating stimuli on training and on performance assessment

ABSTRACT

Investigating ways in which we can improve motor skill learning has received a considerable amount of interest across scientific disciplines such as sports, music, and rehabilitation. In the past, much research focused on the effects of repetition on the execution of motor tasks. More specifically, research on 'contextual interference' has examined the effects of blocked practice (i.e. practicing the same tasks on consecutive blocks) versus random practice (i.e. practicing different tasks on consecutive blocks) on learning motor skills. They found that groups which practiced randomly performed poorer during training, but showed better overall performance in later assessments. Although there is an extensive amount of literature investigating this contextual interference effect at the block level, this effect has not yet been studied at the individual trial level. Here, we examined the effects of switching versus repeating consecutive trials during practice on skill learning and performance. We found that a "Switch Group", who experienced different stimuli on consecutive trials during training, improved to a greater extent than the "Repeat Group", who were presented with repeating stimuli on 20% of consecutive trials during training. Our results replicate and extend the previous finding of the beneficial effects of random as compared to blocked practice on performance. More specifically, trial-to-trial switching during training is favorable with regards to skill learning and performance. This shows that simple behavioral manipulations can lead to significant benefits in the process of skill learning. This approach could potentially be applied to improve motor skill learning in numerous fields.

NEW & NOTEWORTHY

Numerous studies have shown that performing different tasks, rather than repeating the same task, across consecutive blocks leads to better learning. Here we examined whether the same effect would occur on a trial-to-trial level. Our "Switch Group" who responded to different stimuli on consecutive trials learned more than our "Repeat Group" who responded to the same stimuli on 20% of consecutive trials. This shows that a simple and easily applicable behavioral manipulation can enhance learning.

Keywords: Repetition priming; motor skill learning; motor performance; Arbitrary Visuomotor Association Task; speed-accuracy trade-off

INTRODUCTION

It is widely known that with practice the performance of a task or skill improves (Magill and Anderson 2013). Over the years, many studies have investigated different methods to improve skill learning (for example, changing feedback (Rhoads et al. 2014; Wulf et al. 2010), applying brain stimulation (Reis et al. 2009; Galea et al. 2011; Hardwick and Celnik 2014; but see also Vallence et al. 2013; Lopez-Alonso et al. 2015; Lopez-Alonso et al. 2018), and manipulating awareness (Kal et al. 2018)). In the late 21st century, much research focused on the consequences of repetition while executing a motor task (Fecteau and Munoz 2003; Gupta and Cohen 2002). Repetition priming is an implicit memory phenomenon (Gupta and Cohen 2002) and refers to the facilitation in processing a stimulus as a result of previous exposure to this stimulus (Schwartz and Hashtroudi 1991). Terms such as "facilitation of return" (Tanaka and Shimojo 1996) or "priming of pop-out" (Maljkovic and Nakayama 1994; Fecteau 2007) are also used to refer to this phenomenon.

<u>Trial by trial effects of repeating of stimuli</u>

Much research has investigated the consequences of repeating a stimulus on the subsequent action. Bertelson (1961) found that reaction times were shorter on repeated than on non-repeated trials when the time-lag between the stimulus presentation and reaction action was short, suggesting that choice processes involve a favorable effect of repetition.

The effect of repeating stimuli has been investigated in the priming of pop-out literature. Priming of pop-out refers to the fact that "the feature defining the target on the previous trial should attract attention on the next trial" (Fecteau 2007). Maljkovic and Nakayama (1994, 1996) observed favorable effects of repeating the features of a stimulus. More specifically, in separate experiments, they found that the reaction times for stimuli presented at the same position were shorter than those presented at different positions (Maljkovic and Nakayama 1996), and that observers were faster to respond when the color was repeated on two consecutive trials in comparison with when the color had changed (Maljkovic and Nakayama 1994). Repeating the color of a stimulus led to the same results described by Tanaka and Shimojo (1996). More specifically, the reaction time of the next trial was shorter when the color was repeated. These studies highlight the fact that repeating consecutive trials leads to beneficial effects on performance.

The previously described studies all examined the influence of repeating stimuli on the reaction times. Other studies looked at different outcomes to investigate the effect of the previous trial, such as physical execution and transfer through observation (Jax and Rosenbaum 2007; Griffiths and Tipper 2009; Hardwick and Edwards 2011, 2012). Jax and Rosenbaum (2007) used a hand reaching task where participants made movements between a start and target location with or without presentation of an obstacle. Hand path priming was present when obstacles had appeared in the previous trial. When an obstacle was present, the participant avoided it; however, once the obstacle was removed, participants still showed a more curved hand trajectory on the following trial. Moreover, there exists converging evidence that the effect of the previous trial transfers between people (Griffiths and Tipper 2009; Hardwick and Edwards 2011). Griffiths and Tipper (2009) demonstrated that when a person observes another person reaching over an obstacle, the observer has a higher subsequent reach. Hardwick and Edwards (2011) presented similar results. Their participants observed an experimenter grasp an object either normally or with an exaggeratedly high reaching action. Results demonstrated that the movements of the participants took over aspects of the observed reaching action. Taken together, these results show that repetition priming extends beyond reaction times, and can occur through both physical execution and observation of action.

In summary, it is found that the repeating of stimuli facilitates the outcome of the subsequent action and therefore improves performance. More specifically, results show that the reaction time for repeating stimuli is lower than on non-repeating stimuli.

Learning effects of repetition

As described above, repeating stimuli on consecutive trials leads to lower reaction times. Notably, easier tasks take less time to complete (Fitts 1954) and require less reaction time (Hick 1952; Hyman 1953). This suggests that repetition across consecutive trials may make completing a task much easier. This idea has previously been investigated in research on random versus blocked practice. This research shows that people who complete "blocked practice" (practicing the same variant of a task across consecutive blocks) compared to "random practice" (practicing different variants of a task across consecutive blocks) show better performance during the learning phase (Pauwels 2017). Yet, on the contrary, even though the random practice group showed poorer performance during training, their performance was better than the blocked group after a retention period (Pauwels et al. 2014). This phenomenon is known as the contextual interference effect and was first demonstrated by William Battig in 1979. Several studies have reported beneficial effects of random compared to blocked practice: Goode and Magill (1986) showed that performance of a badminton serve after a retention period was better following a period of random compared to blocked practice; Smith and Davies (1995) found that the high contextual interference group outperformed the low contextual interference group in both retention and transfer tests when performing respectively a full and half kayak roll regardless of the direction of the roll; Pauwels et al. (2014) showed that error scores for all frequency ratios were lower in the retention period for the random compared to the blocked practice group. Numerous other studies replicated the same pattern of results (Magill and Hall 1990). Even though a random practice schedule (higher levels of contextual interference) as compared to a blocked practice schedule leads to detrimental effects (poorer performance) during the acquisition phase, long-term retention and transfer will be enhanced (Magill and Hall 1990). It has been proposed that practicing a harder task challenges you more and thus leads to better long-term effects on performance (Guadagnoli and Lee 2004), which has been suggested to underlie the effects of contextual interference (Pauwels et al. 2014).

While numerous studies have investigated the effects of repetition on learning at the block level, this effect has not yet been examined at the individual trial level. In the current study, we aim to investigate the effects of switching between and repeating the same stimuli during learning on performance using an arbitrary visuomotor association task (Hardwick et al. 2018). We hypothesize that repeating the same stimuli will lead to a better performance during training, but that participants would show a poorer level of overall skill in later assessments. This effect might be due to the fact that repeated trials are less challenging and thus lead to a lower quality of practice, which results in a detrimental performance level on later assessments. The hypothesis will be tested by comparing the results of two groups of participants; a “Switch Group” that experiences different stimuli on consecutive trials, and a “Repeat Group” that frequently experiences repeated stimuli on consecutive trials.

MATERIALS & METHODS

Participants

A total of 39 young and healthy participants were recruited for the study. Overall, data from eight participants were excluded from the study. Three participants were excluded as they did not properly follow the instructions (these participants did not make enough responses at the same time as the fourth beep during forced response conditions, see Materials & Methods). A further five participants were excluded due to errors in data acquisition. This left a total sample of 31 participants (mean age = 21.7, age range = 18.4–25.3). Subjects were randomly assigned to either of two groups. The "Switch Group" (n = 15, women = 10, mean age = 21.8, lefthanded = 3), who trained without repetition of consecutive trials, and the "Repeat Group" (n = 16, women = 11, mean age = 21.6, lefthanded = 3), who were presented with repeated stimuli on 20% of consecutive trials during training (Figure 1c). Participants were not aware of the division of the groups. The two groups did not differ significantly with regards to handedness (t_{29}=0.03, p=0.933), gender (t_{29}=0.06, p=0.905), and age (t_{29}=4.38, p=0.663) (Table 2, Supplementary Materials). All participants gave written informed consent before the start of the experiment. The study was approved by the local ethical committee of the University of Leuven (KU Leuven), Belgium. Participants received financial compensation (€20) for their participation.

General Procedures

Participants performed a finger pressing task (Arbitrary Visuomotor Association Task, Hardwick et al. 2018) on their computer for five consecutive days (Figure 1a). They had to respond to the appearance of one out of four stimuli by pushing a specific key (F, T, Y, or J) on their computer keyboard with either the index, middle, ring, or little finger of their dominant hand (Figure 1b). In the experiment, four different types of conditions were completed: familiarization, criterion test, rapid response, and forced response conditions.

Familiarization tasks

During the familiarization blocks, participants got used to performing the task. These tasks were similar to the main task, but here participants had to respond to pictures of hands, rather than arbitrary stimuli. In these pictures, one finger was highlighted. Participants had to respond with the corresponding finger (Figure 2a). During these familiarization blocks, participants performed both the rapid response task and forced response task, each of which are explained in more detail below.

Criterion test block

In this block, participants learned the correct mapping of the keys and stimuli through trial and error. A stimulus appeared on screen and participants had to learn which key it corresponded to. There were four different symbols and each symbol corresponded to a different key. The mapping of the keys and stimuli was counterbalanced across participants. During this block, participants were instructed to focus on learning the correct mapping of the symbols and keys. Therefore, they were instructed that they could take as much time as they needed (i.e. they did not have to execute this block as quickly as possible). The block ended as soon as a participant had made 5 consecutive correct responses to each of the four stimuli (i.e. 20 trials in total).

Rapid response blocks

In rapid response trials, participants had to respond to the stimulus as quickly as possible using the corresponding finger. The goal was to complete the block as quickly and as accurately as possible. Whenever a participant made a correct response, they continued with the next trial (note that there was a 300ms delay in between trials). However, if a participant made a wrong response, a red box appeared around the stimulus and the participant had to wait 1000ms before he or she could make a response again (referred to as a “one second penalty” when explaining the condition of the task to the participants). Hence, participants were instructed to respond as quickly as possible, but to find a balance between speed and accuracy.

Forced response blocks

During the forced response blocks, participants heard a series of four equally spaced beeps (Figure 2b). They were instructed to time their response, so it would coincide with the fourth beep. The stimuli appeared at a random time between the first and fourth beep. This allowed effective control over the amount of time participants had to process the stimulus and prepare their response. The earlier the stimulus appeared on screen, the more time the participants had to prepare their response. On the contrary, the later the stimulus appeared on screen, the less time the participants had to prepare their response, and the more difficult it became to make a correct response. Whenever the stimulus appeared relatively late in the series of beeps, participants had more difficulties in preparing the correct response and in some cases had to guess (Figure 2c,d). Participants were instructed that their highest priority was to respond at the same time as the fourth beep, and that while they should aim to be accurate wherever possible, this should not come at the cost of missing the deadline.

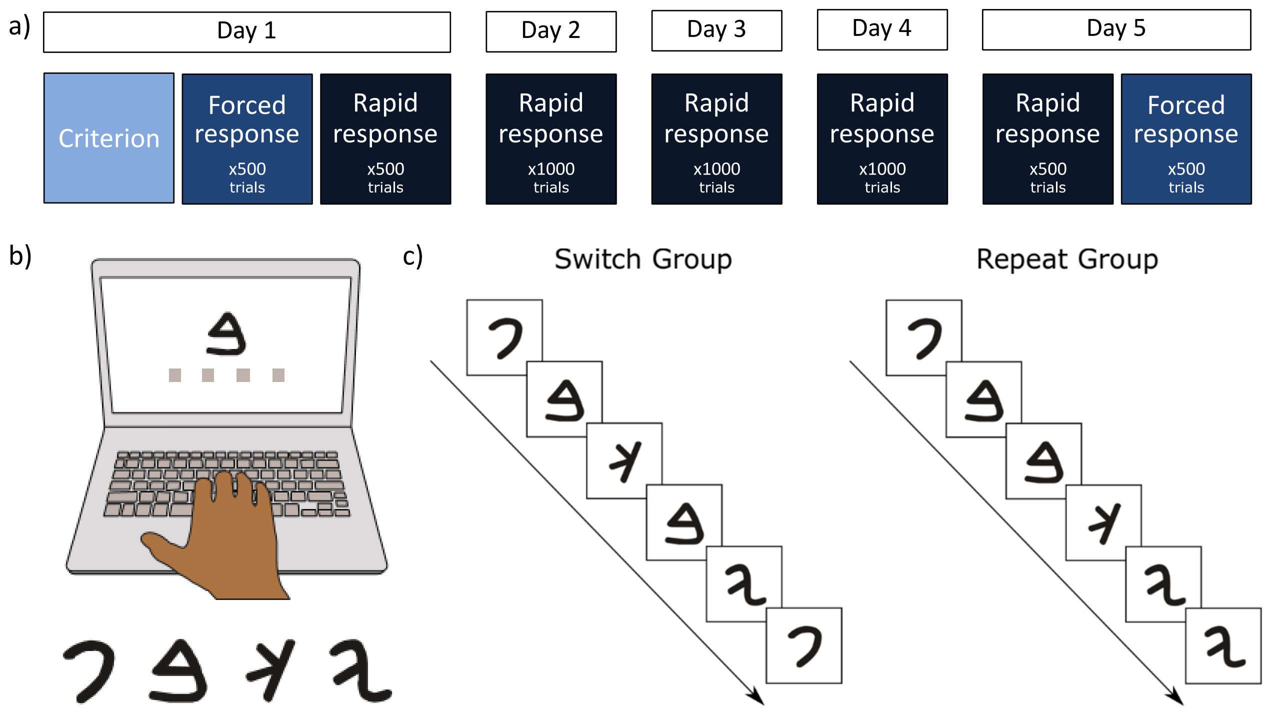

Figure 1. Task procedure and setup. a) Task procedure: On day 1, participants came to the lab and were familiarized with the task (not presented in figure, see Materials & Methods - General Procedures for further details). Hereafter, in the criterion test block, they learned a fixed mapping between stimuli and keys that was used throughout the rest of the experiment. They then used the same mapping to execute 500 forced response trials and 500 rapid response trials. On days 2, 3, and 4, participants executed 1000 rapid response trials per day at home using the same mapping. On day 5, participants came back to the lab. They first were presented with 500 rapid response trials, after which their performance was measured during 500 forced response trials (again, all 1000 trials used the same mapping). b) Task setup: A stimulus appeared on screen and participants had to respond by pressing a key with a certain finger. Stimuli were letters of the Phoenician Alphabet. c) Group difference: The content of the rapid response blocks (training blocks) differed between groups. The "Switch Group" did not experience repeating stimuli on consecutive trials, whereas the "Repeat Group" was presented with repeating stimuli on 20% of consecutive trials.

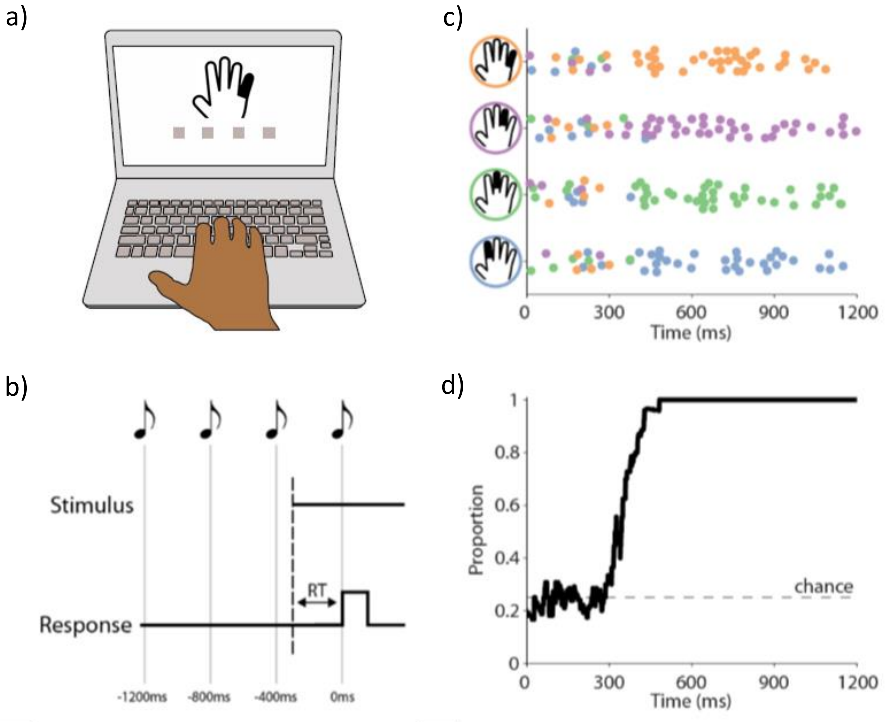

Figure 2. a) Familiarization task. Pictures of hands with one finger highlighted were shown on screen and participants had to respond with the corresponding finger. b) Forced response paradigm. Visual representation of the sequence of four beeps with stimulus representation and response onset. A stimulus appeared at a random time between the first and fourth beep. Participants had to respond synchronously with the fourth beep. Here the reaction time (RT) refers to the time between stimulus presentation and the first key press participants made. c) Forced response example data. Data from an example participant on the forced response familiarization task. Participants responded to pictures of hands in which one finger was highlighted by pressing the corresponding finger on the keyboard. Illustrations of these stimuli are presented on the y-axis. Each dot represents the participant's response on a single trial (jitter added to y-axis to allow for visualizing multiple responses at the same time). Each color represents the finger the participant responded with. Note that when the reaction time was low, all colors are mixed indicating that a participant did not have enough time to prepare the correct response. However, when the reaction time increased, the colors became more consistent, indicating that the participant was able to make a correct response. d) Data from panel c converted into a speed-accuracy trade-off curve. A sliding window (running average across a 100ms window) is used to present the accuracy for a given time. Note that at times <300ms, responses were by chance meaning that participants did not have enough time to process the stimulus and hence pressed a random key. After 300ms, the level of accuracy increased with time. The time at which the color became the same in part c closely matches the time at which the proportion of correct responses reached a score of 1 in part d.

PROTOCOL

Day 1

Session 1 started with a brief introduction to the task. During the familiarization task, participants got the opportunity to get used to the task in rapid response and timed response trials with practice to the hand stimuli (2 blocks of each trial type, 100 trials per block) (Figure 2a). After the task familiarization trials, participants executed the criterion training block where they had to learn the correct mapping between the stimuli and keys. Subsequently, participants executed 5x100 trial blocks of forced response trials in which the baseline performance was measured. This was done to get an initial measure of the speed-accuracy trade-off before training. Finally, participants trained on 5x100 trial blocks of rapid response trials to arbitrary stimuli.

Days 2 – 4

During the second, third, and fourth session, participants executed the training blocks. Each session consisted of 10x100 trial blocks of rapid response trials to arbitrary stimuli. The same stimulus-response associations that participants learned during the criterion training block on day 1 were used.

Day 5

The first five blocks were rapid response trials to arbitrary stimuli. This data was collected to get a measure of performance on the final day of training with this trial type. The final five blocks were timed response trials to arbitrary stimuli. This data was collected to get a final empirical measure of the speed-accuracy trade-off after training.

DATA ANALYSIS

Criterion Test Trials

During the criterion test block, two measures were extracted. Firstly, the number of trials participants needed to reach the criterion level (i.e. the number of trials a participant needed to make five correct responses to each of the four stimuli) was measured. Secondly, the reaction time for each response was recorded (note that participants were instructed that there were no time restrictions in this block). Independent samples t-tests were used to statistically compare both measures between groups.

Forced Response Trials

During the forced response trials, we extracted the time participants had to respond to the visual stimuli and whether their response was correct or incorrect. A previously established model based on a log likelihood fit was used to analyze the data (Haith et al. 2016; Hardwick et al. 2018). This model is used to quantify the speed-accuracy trade-off. It assumes that if you have more time you should transition from making random responses, to making responses based on your ability to process the stimulus. It is a 4-parameter model with a sigmoidal shape. The first two parameters represent the asymptotic probability of producing the correct response at low reaction times and at longer reaction times. The other two parameters look at the slope and center of the transition between the two asymptotes. Previously, the center point of the speed-accuracy trade-off curves has been used to compare performance on the forced response trials (Hardwick et al. 2018). Therefore, we used the center parameter to statistically compare the initial and final performance assessments. A mixed model ANOVA was used to statically compare center of the curves between groups. Post-hoc analyses (independent samples t-tests) were run to specify the direction of the found differences.

We also used a sliding window to visualize this time-varying likelihood of the accuracy level across trials. Average responses were taken over a 100ms window (Figure 2d). This is consistent with previous research looking at the speed-accuracy trade-off measure (Haith et al. 2016; Hardwick et al. 2018).

Rapid Response Trials

In these trials, performance was measured using reaction times and errors. Reaction time was defined as the time between stimulus onset and the time that a participant made their first response. For each trial, we assessed the reaction time and error on the first attempt response. For each block, the median reaction times and number of errors were calculated. Then, the average was taken across groups. A mixed model ANOVA was used to statistically compare reaction times and number of errors between groups. Post-hoc analyses (independent samples t-tests) were run to specify the direction of the found differences.

Next, for the “Repeat Group”, extra analyses were run to examine non-repeating versus repeating trials. A repeated measures ANOVA was used to statistically compare reaction times and number of errors between trial types. Post-hoc analyses (paired samples t-tests) were run to specify the direction of the found differences.

RESULTS

Criterion Test Trials

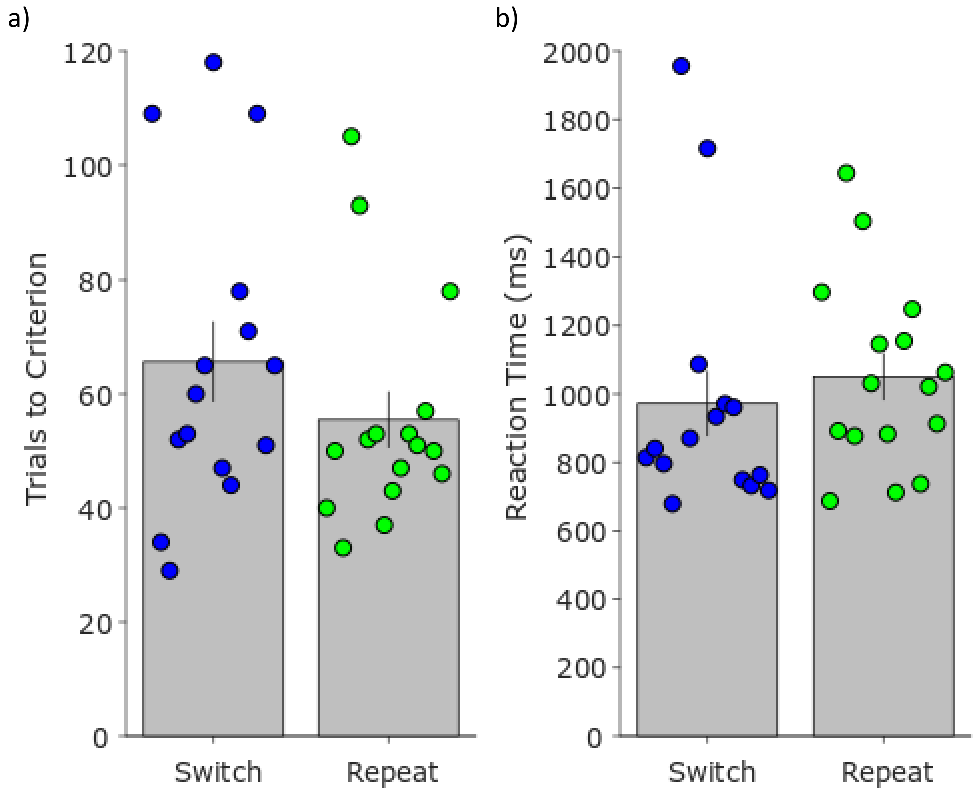

Figure 3. Criterion measures. a) The number of trials participants needed to reach the criterion. b) The average reaction times on the trials during the criterion training block. In each figure, the grey bars represent the average number of trials (a) or reaction time (b) for both the "Switch" and "Repeat Group". Error bars represent the standard error of the mean. Dots represent individual data of participants in each group.

During the criterion training block, participants learned the mapping of the symbols to the different keys. Both groups did not differ significantly by the number of trials they needed to reach the criterion (t_{29}=1.65, p=0.243) (Table 4, Supplementary Materials). They did not differ significantly either by the average reaction times during the criterion block (t_{29}=0.17, p=0.507) (Table 4, Supplementary Materials). Consequently, there was no significant difference between the groups at baseline when they learned the stimulus-response associations.

Forced Response Trials

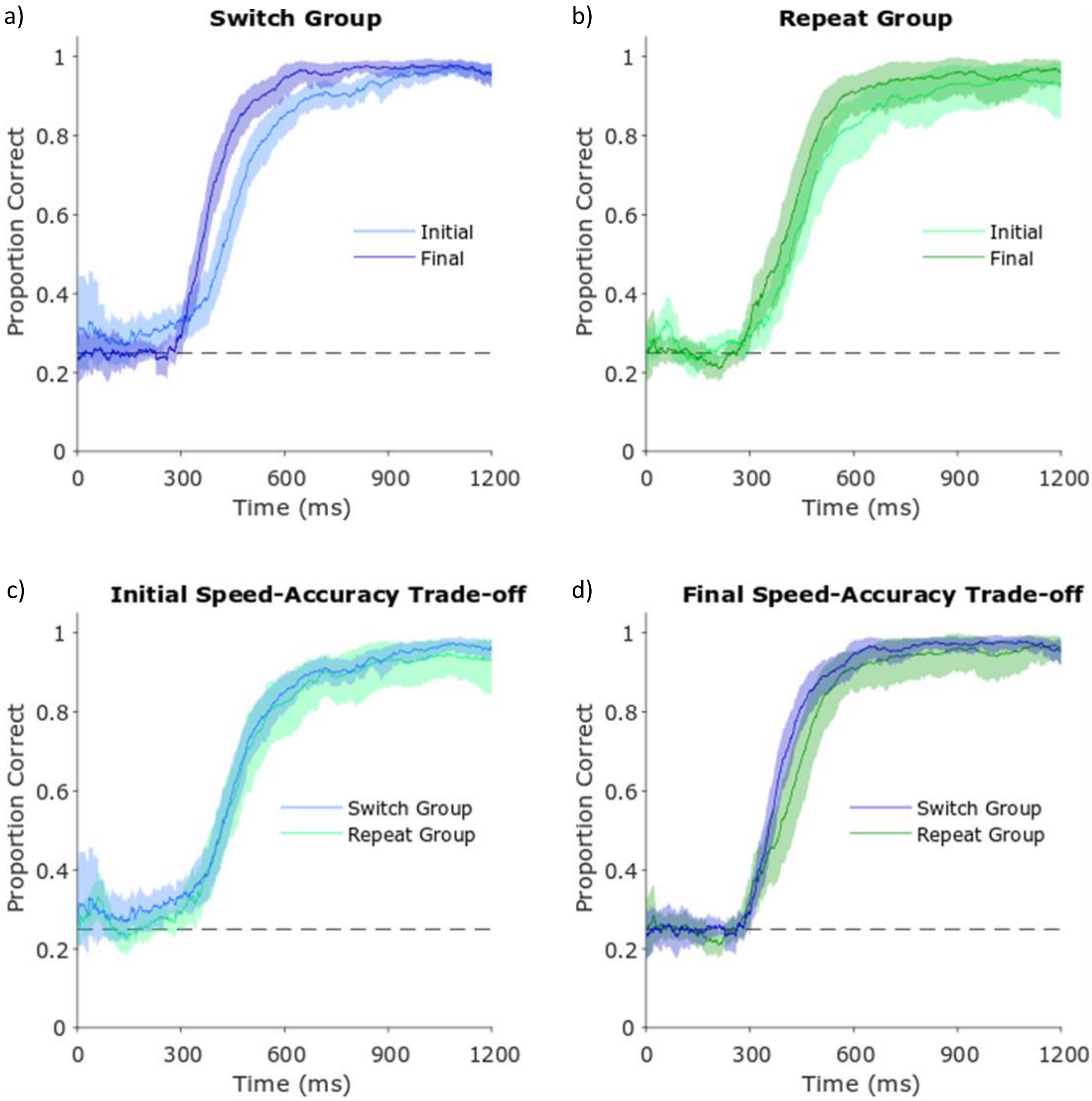

Figure 4. Speed-accuracy trade-offs. a) Initial versus final comparison of the speed-accuracy trade-off for the "Switch Group". b) Initial versus final comparison of the speed-accuracy trade-off for the "Repeat Group". c) Comparison of the initial speed-accuracy trade-offs between groups. d) Comparison of the final speed-accuracy trade-offs between groups. In all figures, shaded areas represent bootstrapped 95% confidence intervals.

Concerning performance measures, we generated speed-accuracy trade-off curves using data from the forced response trials collected on the first and last day of the experiment. A mixed model ANOVA on the center of the curve revealed a significant main effect of day ($F_{1,29}$=64.83, p<0.005) (Table 6, Supplementary Materials). All participants improved their speed-accuracy trade-off after training (as visualized by a shift of the curve towards the left - see Figure 4). The amount of improvement, however, was different between groups. The mixed model ANOVA revealed a significant day by group interaction ($F_{1,29}$=5.18, p=0.03) (Table 6, Supplementary Materials) (Figure 4a,b). For the initial assessment, both groups showed a similar speed-accuracy trade-off curve (Figure 4c). This was illustrated by an independent samples t-test on the center of the curves on the first day which revealed a non-significant difference between groups (t_{29}=0.13, p=0.901) (Table 7, Supplementary Materials). For the final assessment, participants in the “Switch Group” (397ms) needed less time in order to reach a certain level of accuracy in comparison with the “Repeat Group” (432ms) (Table 5, Supplementary Materials) (Figure 4d). An independent samples t-test on the center of the curves on the final day of assessment revealed a trend towards significance (t_{29}=1.93, p=0.062) (Table 7, Supplementary Materials). When comparing the amount of improvement between the initial and final day of assessment on the centers of the curves, participants in the “Switch Group” improved to a greater extent (73ms) than the “Repeat Group” (41ms) (Table 5, Supplementary Materials). This was shown by an independent samples t-test which revealed a significant difference between groups on the amount of improvement on the centers of the curves (t_{29}=-2.28, p=0.03) (Table 7, Supplementary Materials).

In the supplementary materials, model fits to the individual participant data are presented in Figures 1 and 2.

Rapid Response Trials Showing Training Data

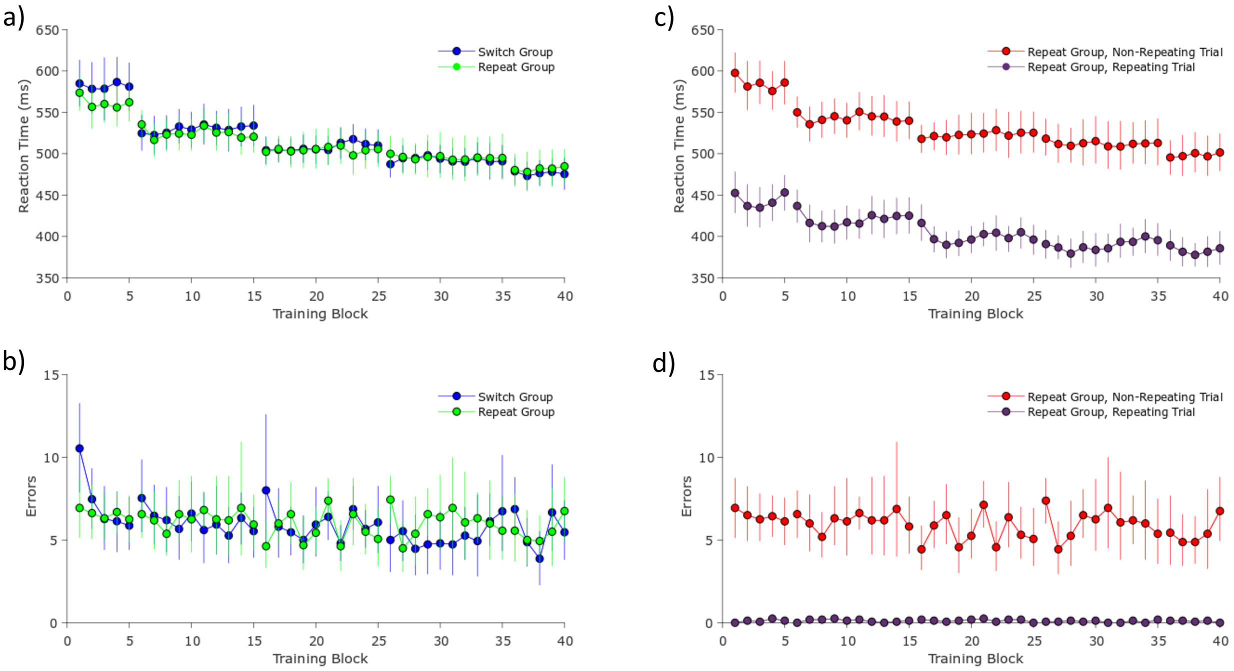

Figure 5. <u>Training Measures</u>. a) Plot of the median reaction times during rapid response trials for both the "Switch" (blue) and the "Repeat" (green) group. b) Plot of the number of first attempt errors during rapid response trials for both the "Switch" (blue) and the "Repeat" (green) group. c) Plot of the median reaction times during rapid response trials for both non-repeating (red) and repeating (purple) trials of the "Repeat Group". d) Plot of the number of first attempt errors during rapid response trials for both non-repeating (red) and repeating (purple) trials of the "Repeat Group". In all figures, error bars represent bootstrapped 95% confidence intervals.

A mixed model ANOVA on participants' reaction times revealed a significant main effect of day ($F_{1,29}$=185.28, p<0.001) showing that participants improved their performance with practice (Table 9, Supplementary Materials). As the day by group interaction showed a trend towards significance ($F_{1,29}$=3.45, p=0.073) (Table 9, Supplementary Materials), we ran post-hoc tests to examine whether there were differences between groups on both days. An independent samples t-test on the first day revealed a non-significant difference between the "Switch" and "Repeat Group" (t_{29}=1.01, p=0.319) (Table 10, Supplementary Materials). The same result was found on the last day; an independent samples t-test revealed a nonsignificant difference between the "Switch" and "Repeat Group" (t_{29}=-0.36, p=0.720) (Table 10, Supplementary Materials). Finally, when comparing the amount of improvement between the first and the last day on the reaction times, participants in the "Switch Group" improved to a greater extent (110ms) than the "Repeat Group" (80ms) (Table 8, Supplementary Materials). This was shown by an independent samples t-test which revealed a trend towards significance (t_{29}=1.90, p=0.067) (Table 10, Supplementary Materials).

The second variable of interest for the training blocks was the number of errors. A mixed model ANOVA on participants' errors revealed a significant main effect of day ($F_{1,29}$=6.95, p=0.013) indicating that participants made less errors with practice (Table 9, Supplementary Materials). By contrast, the day by group interaction effect was not significant ($F_{1,29}$=0.45, p=0.506) indicating that both groups improved their number of errors to the same extent (Table 9, Supplementary Materials).

As we were interested in examining the difficulty level of non-repeated versus repeated trials, we ran some specific analyses with regards to the data of the "Repeat Group". More specifically, reaction times and errors were compared for non-repeated and repeated trials. A repeated measures ANOVA on reaction times revealed a significant main effect of day ($F_{1,15}$=256.62, p<0.001) showing that performance on both trial types improved with practice (Table 12, Supplementary Materials), and a significant main effect of trial type ($F_{1,15}$=99.29, p<0.001) showing that performance significantly differed between both trial types (Table 12, Supplementary Materials). The repeated measures ANOVA also revealed a significant day by trial type interaction ($F_{1,15}$=12.15, p=0.003) indicating that improvement significantly differed between trial types (Table 12, Supplementary Materials). A paired samples t-test on the reaction time data of the repeated group on the first day revealed a significant difference between the non-repeated and repeated trials (t_{15}=-10.32, p<0.001) with non-repeated trials (585ms) showing a higher reaction time than repeated trials (444ms) (Tables 11 & 13, Supplementary Materials). The same result was found for the reaction time data of the repeated group on the last day; a paired samples t-test revealed a significant difference between the non-repeated and repeated trials (t_{15}=-8.77, p<0.001) with non-repeated trials (498ms) showing a higher reaction time than repeated trials (383ms) (Tables 11 & 13, Supplementary Materials). Finally, when comparing the amount of improvement between the first and the last day on the reaction times, participants improved to a greater extent on the non-repeated trials (87ms) compared to the repeated trials (58ms) (Table 11, Supplementary Materials). This was shown by a paired samples t-test which revealed a significant difference between trial types on the amount of improvement on the reaction times (t_{15}=-3.48, p=0.003) (Table 13, Supplementary Materials).

A second analysis on the "Repeat Group" data was executed to examine differences in the number of errors between non-repeated and repeated trial types. The repeated measures ANOVA revealed a significant main effect of trial type ($F_{1,15}$=70.68, p<0.001) indicating that the number of errors significantly differed between non-repeated and repeated trials (see Figure 5d) (Table 12, Supplementary Materials). However, there was neither a significant main effect of day ($F_{1,15}$=2.17, p=0.162) nor a significant day by trial interaction ($F_{1,15}$=12.15, p=0.219) (Table 12, Supplementary Materials). A paired samples t-test on the average number of errors across days 1 and 5 revealed a significant difference between the non-repeated and repeated trials (t_{15}=-8.407, p<0.005) with non-repeated trials showing a higher number of errors (5,96) than repeated trials (0.1) (Tables 11 & 13, Supplementary Materials).

DISCUSSION

The present study examined the impact of repeating consecutive trials during practice on learning using an arbitrary visuomotor association task (Hardwick et al. 2018). While previous studies on contextual interference have examined the effects of block-to-block changes, this is, to the best of our knowledge, the first study to examine the effects of trial-to-trial changes. We found that, after practice, the "Switch Group", who always experienced different stimuli on consecutive trials (hence, contextual interference at the individual trial level), performed better than the "Repeat Group", who experienced consecutive repeating stimuli on 20% of the trials.

Interpretation Forced Response Results

A speed-accuracy trade-off measure was used to look at the performance. While both groups needed less time to obtain a given level of accuracy after five days, the "Switch Group" improved to a greater extent. This is in line with previous studies investigating the impact of blocked versus random practice on performance (Goode and Magill 1986; Smith and Davies 1995; Pauwels et al. 2014; Magill and Hall 1990). The question remains, however, why the "Switch Group" experienced a greater improvement on the forced response task than the "Repeat Group". It could be that the "Switch Group" showed a greater improvement simply because they executed a harder task during practice. Evidence from the training measures of the "Repeat Group" shows that both the reaction times and error rates were lower for repeating than non-repeating trials. This shows that the task of the "Repeat Group" was easier than the task of the "Switch Group", as the latter was not presented with any repeating trials. This is in line with previous research indicating that repeating the same response facilitates performance (Bertelson 1961; Maljkovic and Nakayama 1994, 1996; Tanaka and Shimojo 1996). Therefore, because the "Repeat Group" practiced an easier version of task, it could be that they were less challenged. As described by the Challenge Point Framework, in order to learn more, you need to execute a harder task as this challenges you more (Guadagnoli and Lee 2004). This is supported by both behavioral and neural results. Pauwels et al. (2014) stated that receiving contextual interference at the block level (which is harder than blocked practice) adds a challenge to the learning process (i.e. increased cognitive effort and processing) which leads to beneficial learning effects. Hence, it could be that receiving contextual interference at the individual trial level encompasses the same beneficial learning effects as this makes the task harder.

Interpretation Rapid Response Training Results

While both groups differed with regards to the speed-accuracy trade-offs from the forced response trials, they did not differ during training with regards to both the reaction time as well as the error rate data. There are, however, multiple explanations for this apparently paradoxical result. First, when comparing the training data between groups, it is important to note that both groups trained on different versions of the same task. The “Switch Group” was presented with changing symbols on each trial, whereas the “Repeat Group” was presented with repeating symbols on 20% of the trials. As discussed above, the training task was easier for the “Repeat Group”; therefore, a direct comparison between their data during training may not be reflective of an actual performance difference between the groups. Second, the participants experienced a relatively short training period. If the training period had been longer, the “Switch Group”, which trained on the harder version of the task, might have had more opportunity to improve than the “Repeat Group”. Future research could examine this point within a longer period of training. Third, it can be difficult to interpret the data from a task where speed and accuracy are considered separately. As speed and accuracy are both inherently linked to the overall performance of a skill, this allows some variability between participants. While participants were instructed to respond as quickly and as accurately as possible to the symbols, it might be that they interpreted this differently; some might focus more on speed at the cost of accuracy, while others might favor accuracy at the cost of speed. Even though no significant difference was found, a hint of this discrepancy was seen in the criterion data. The “Switch Group” favored speed (i.e. had a lower average reaction time but needed more trials to reach the criterion), whereas the “Repeat Group” favored accuracy (i.e. needed less trials to reach the criterion but had a higher average reaction time). It is therefore hard to assess skill when interpreting data where both speed and accuracy can vary freely (Reis et al. 2009; Shmuelof et al. 2012). Hence, Reis et al. (2009) suggested to quantify performance on a skill using a speed-accuracy trade-off; this combined measure of speed and accuracy better relates to a change in skill. Therefore, in this study, the forced response measure was used to get a cleaner assessment of overall performance. Controlling the time participants had to prepare their responses (by varying the onset of the visual stimulus), allowed us to assess accuracy without the influence of confounding differences in response speed. As such, looking at the speed-accuracy trade-off data gave us a better way to interpret participant performance.

Broader Context

Notably, there has been much research investigating the effects of repetition on learning through contextual interference (for reviews see Magill and Hall 1990; Brady 1998; Merbah and Meulemans 2011). By comparison, to the best of our knowledge, studies investigating trial-to-trial effects of repetition on learning have not been subject to much research (we did not find any previous literature on this subject). This seems surprising as there has been great interest in improving the learning process. Previous work has tried to improve learning rates in relatively complex approaches including non-invasive brain stimulation (Reis et al. 2009; Galea et al. 2011; Hardwick and Celnik 2014; but see also Vallence et al. 2013; Lopez-Alonso et al. 2015; Lopez-Alonso et al. 2018) and drugs (Pugliese 1973). Critically, if you could improve learning through simple behavioral manipulations (which are easy and cost effective to implement), and on top of that gain benefits using neuromodulatory interventions that directly target brain mechanisms underlying learning, this could result in larger performance benefits.

Implications

Our results showed that practicing without repeating consecutive trials led to a greater improvement on skill performance. This finding sheds light on the way in which we can improve learning by optimizing this process at the behavioral level. Improving the rate at which we learn also has implications in a broader context, including fields such as sports, playing musical instruments, and rehabilitation. Based on the work of Ericson et al. (1993), you need an extensive amount of “deliberate practice” to become an expert in executing movement skills. If we could improve learning, that would be beneficial in terms of efficiency (i.e. you would need less time to learn a given skill). Enhancing the rate of learning could also specifically be beneficial during recovery from stroke. It is shown that most recovery from stroke is made within the “acute phase” within the first three months after the stroke (Xu et al. 2017). During this critical time period, the brain naturally reorganizes itself by means of neuroplastic mechanisms, which leads to a period of “spontaneous biological recovery” (Zeiler and Krakauer 2013). Therefore, it has been argued that training during this critical period would result in an improved overall recovery due to the spontaneously occurring neuroplastic processes interacting with physical practice (Zeiler and Krakauer 2013). Taken together, this underlines the importance of developing approaches to improve the rate of learning.

Strengths and Limitations

Finally, we should address some strengths and limitations of the current study. It might be proposed that the amount of control we had over the participants' execution of the task is a limitation of our design. On the first and last day, participants performed the task in the laboratory, whereas on days two, three, and four, participants practiced the task on their own at home. It could be argued that practicing the task in these different contexts could have had an impact on participants' performance (i.e. the presence of an experimenter has previously been shown to affect participants' performance (for a review see McCambridge et al. 2014)). However, as the overall procedure was the same for both groups, it seems unlikely that this would confound our results. As such, allowing participants to train at home provided a pragmatic solution to conduct a 5-day experiment. With regards to the design of the study, it might be suggested that extending the training period could have resulted in a difference between groups on the training measures. However, this is inconsequential as we still found a difference in the forced response data.

CONCLUSION

This study investigated the effect of switching between trials versus repeating of consecutive trials during practice on the speed-accuracy trade-off measure during performance. It is the first study to implement contextual interference at the individual trial level. We found that the "Switch Group" showed a greater improvement in performance as compared to the "Repeat Group". This finding has potential benefits in the context of skill learning in fields such as sport, music and rehabilitation; random practice at the individual trial level improves the rate at which you learn. Future research is necessary to investigate the neural correlates of the behavioral findings.

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GRANTS

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DISCLOSURES

All authors declared no conflict of interest.

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SUPPLEMENTARY MATERIALS

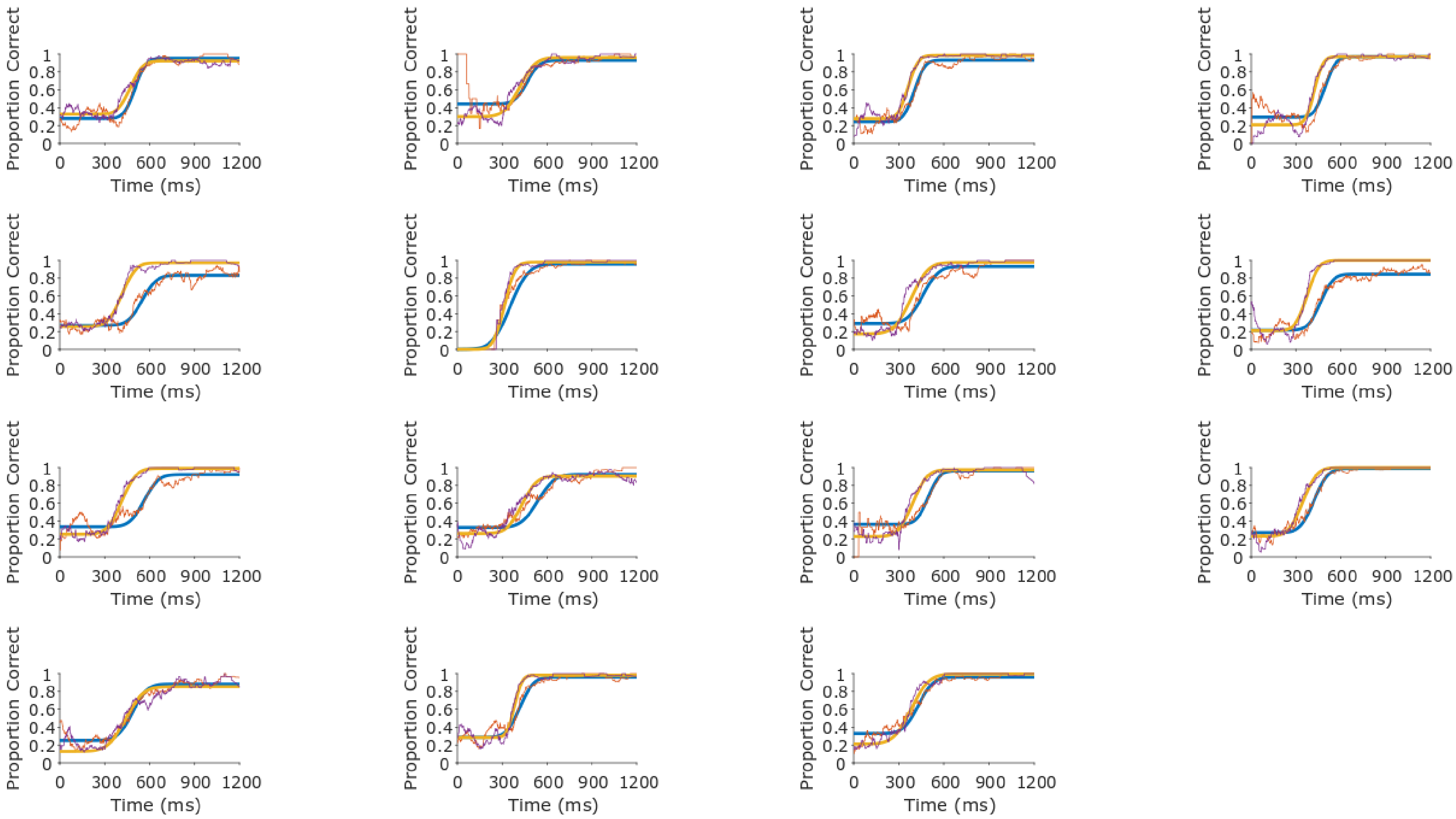

Figure 1. Individual participant data for the “Switch Group”. Individual data for the sliding window (red: initial data; purple: final data) and model fits (blue: initial data; yellow: final data) are plotted.

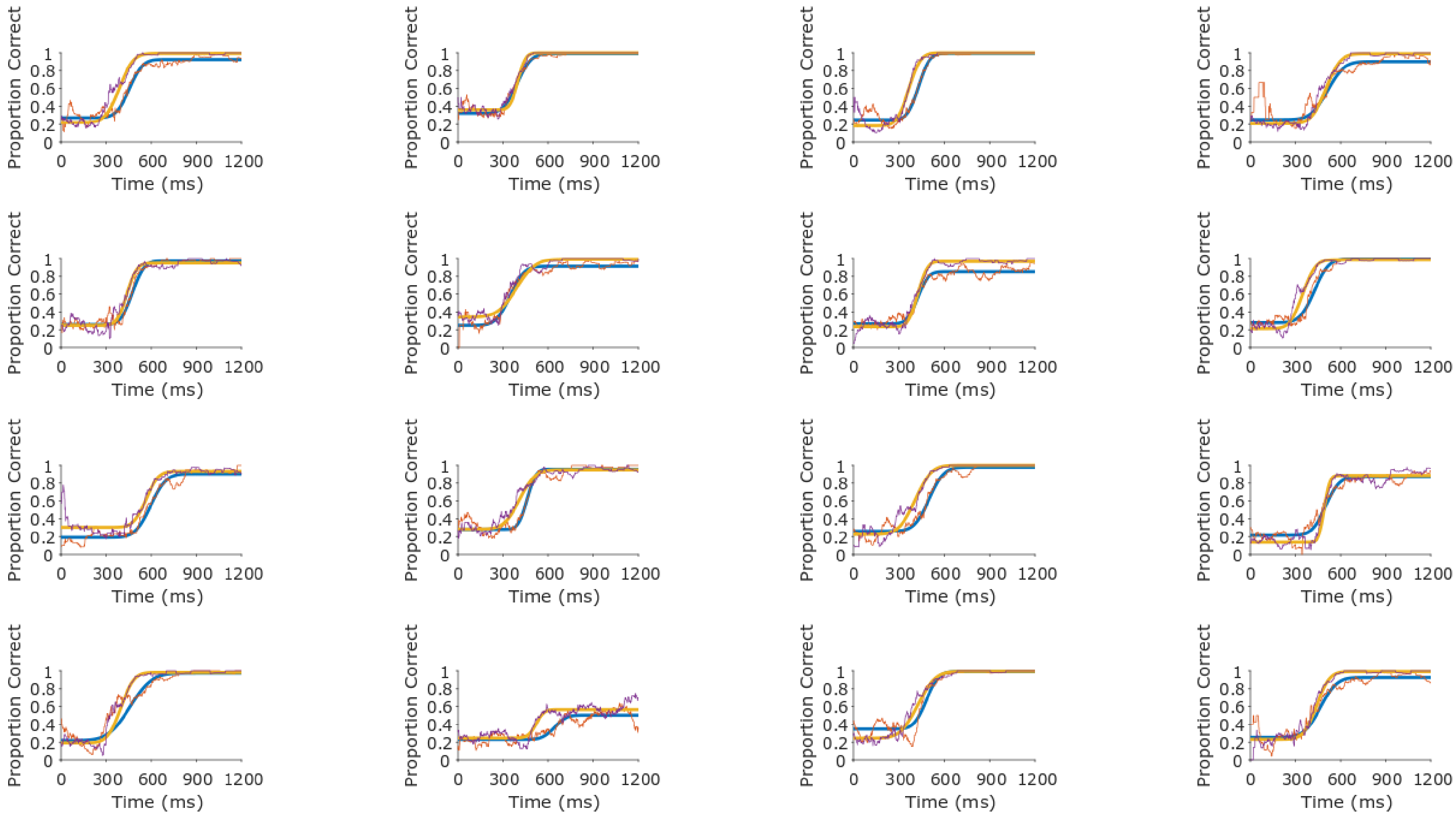

Figure 2. Individual participant data for the “Repeat Group”. Individual data for the sliding window (red: initial data; purple: final data) and model fits (blue: initial data; yellow: final data) are plotted.

Participant Information

Table 1: Descriptive statistics of participant information

	Group	N	Mean	Standard Deviation	Standard Error Mean
Handedness	Switch	15	1.20	0.414	0.107
	Repeat	16	1.19	0.403	0.101
Gender	Switch	15	1.33	0.488	0.126
	Repeat	16	1.31	0.479	0.120
Age	Switch	15	21.8327	1.11139	0.28696
	Repeat	16	21.5845	1.90188	0.47547

Table 2: Independent samples test on participant information

	Levene's test for equality of variances					t-test for equality of means		95% CI of the difference	
	F	**Sig**	**t**	**df**	**Sig (2-tailed)**	**Mean Difference**	**Standard Error Difference**	**Lower**	**Upper**
Handedness	0.029	0.866	0.085	29	0.933	0.012	0.147	-0.288	0.313
Gender	0.057	0.813	0.120	29	0.905	0.021	0.174	-0.334	0.376
Age	4.378	0.045	0.440	29	0.663	0.24817	0.56452	-0.90641	1.40274

Criterion Test Trials

Table 3: Descriptive statistics of criterion measures

	Group	N	Mean	Standard Deviation	Standard Error Mean
Trials to criterion	Switch	15	65.6667	27.30167	7.04926
	Repeat	16	55.5000	19.79562	4.94891
Average reaction time	Switch	15	0.9724	0.37033	0.09562
	Repeat	16	1.0507	0.27401	0.06850

Table 4: Independent samples test on criterion measures

	Levene's test for equality of variances		t-test for equality of means					95% CI of the difference	
	F	**Sig**	**t**	**df**	**Sig (2-tailed)**	**Mean Difference**	**Standard Error Difference**	**Lower**	**Upper**
Trials to criterion	1.651	0.209	1.193	29	0.243	10.16667	8.52408	-7.26704	27.60037
Average reaction time	0.168	0.685	-0.672	29	0.507	-0.07829	0.11648	-0.31652	0.15994

Forced Response Trials

Table 5: Descriptive statistics of forced response measures

	Group	N	Mean	Standard Deviation	Standard Error Mean
Center first day	Switch	15	0.4699	0.05817	0.01502
	Repeat	16	0.4728	0.07126	0.01782
	Total	31	0.4714	0.06419	0.01642
Center last day	Switch	15	0.3967	0.03885	0.01003
	Repeat	16	0.4319	0.05938	0.01485
	Total	31	0.4148	0.05280	0.01244
Improvement	Switch	15	0.0732	0.03743	0.00966
	Repeat	16	0.0409	0.04123	0.01031
	Total	31	0.0571	0.03933	0.00999

Table 6: Mixed model ANOVA on forced response measures

		Type III Sum of Squares	df	Mean Square	F	Sig	Partial Eta Squared
Center	Day	0.050	1	0.050	64.831	0.000	0.691
	Day*Group	0.004	1	0.004	5.176	0.030	0.151
	Error(Day)	0.023	29	0.001			

Table 7: Independent samples test on forced response measures

	Levene's test for equality of variances					t-test for equality of means		95% CI of the difference	
	F	Sig	t	df	Sig (2-tailed)	Mean Difference	Standard Error Difference	Lower	Upper
Center first day	0.069	0.794	0.126	29	0.901	0.00295	0.02346	-0.04503	0.05093
Center last day	1.868	0.182	1.938	29	0.062	0.03520	0.01816	-0.00194	0.07234
Improvement	0.102	0.751	-2.275	29	0.030	-0.03225	0.01418	-0.06124	-0.00326

Rapid Response Trials Showing Training Data

Table 8: Descriptive statistics of rapid response measures

	Group	N	Mean	Standard Deviation	Standard Error Mean
First attempt reaction time day 1	Switch	15	0.5819	0.06202	0.01601
	Repeat	16	0.5617	0.04848	0.01212
	Total	31	0.5714	0.05546	0.01407
First attempt reaction time day 5	Switch	15	0.4763	0.03296	0.00851
	Repeat	16	0.4815	0.04503	0.01126
	Total	31	0.4790	0.03909	0.00989
Improvement	Switch	15	0.1100	0.05000	0.01300
	Repeat	16	0.0800	0.01800	0.00400
	Total	31	0.0950	0.03400	0.01700
First attempt errors day 1	Switch	15	7.2533	3.53389	
	Repeat	16	6.5625	2.57705	
	Total	31	6.8968	3.04494	
First attempt errors day 5	Switch	15	5.5467	3.05237	
	Repeat	16	5.5500	3.61368	
	Total	31	5.5484	3.29807	

Table 9: Mixed model ANOVA on rapid response measures

		Type III Sum of Squares	df	Mean Square	F	Sig	Partial Eta Squared
Reaction time	Day	0.134	1	0.134	185.278	0.000	0.865
	Day*Group	0.002	1	0.002	3.454	0.073	0.106
	Error(Day)	0.021	29	0.001			
Errors	Day	28.621	1	28.621	6.946	0.013	0.193
	Day*Group	1.865	1	1.865	0.453	0.506	0.015
	Error(Day)	119.493	29	4.120			

Table 10: Independent samples test on rapid response measures

	Levene's test for equality of variances		t-test for equality of means					95% CI of the difference	
	F	Sig	t	df	Sig (2-tailed)	Mean Difference	Standard Error Difference	Lower	Upper
First attempt reaction time day 1	0.618	0.438	1.014	29	0.319	0.02020	0.01992	-0.02055	0.06094
First attempt reaction time day 5	2.103	0.158	-0.363	29	0.720	-0.00517	0.01426	-0.03432	0.02399
Improvement	7.889	0.009	1.903	29	0.067	0.02500	0.01300	-0.00200	0.05300

Table 11: Descriptive statistics of rapid response measures ("Repeat Group")

	Group	N	Mean	Standard Deviation	Standard Error Mean
Reaction time day 1	Repeated trials	16	0.4436	0.04717	0.01179
	Non-repeated trials	16	0.5852	0.05235	0.01309
	Total	32	0.5144	0.08707	0.01244
Reaction time day 5	Repeated trials	16	0.3831	0.03458	0.00864
	Non-repeated trials	16	0.4983	0.04810	0.01202
	Total	32	0.4407	0.07154	0.01033
Improvement	Repeated trials	16	0.0581	0.02786	0.00697
	Non-repeated trials	16	0.0869	0.01887	0.00472
	Total	32	0.0725	0.02337	0.00585
Errors*	Repeated trials	16	0.1000	0.12111	0.03028
	Non-repeated trials	16	5.9562	2.80118	0.70030
	Total	32	3.0281	1.46115	0.36529

*Errors = Average number of errors across day 1 and 5

Table 12: Repeated measures ANOVA on rapid response measures ("Repeat Group")

		Type III Sum of Squares	df	Mean Square	F	Sig
Reaction time	Day	0.087	1	0.087	256.624	0.000
	Error(Day)	0.005	15	0.000		
	Trial type	0.264	1	0.264	99.291	0.000
	Error(Trial type)	0.040	15	0.003		
	Day*Trial type	0.003	1	0.003	12.150	0.003
	Error(Day*Trial type)	0.003	15	0.000		
Errors	Day	4.101	1	4.101	2.168	0.162
	Error(Day)	28.369	15	1.891		
	Trial type	548.731	1	548.731	70.677	0.000
	Error(Trial type)	116.459	15	7.764		
	Day*Trial type	3.706	1	3.706	1.644	0.219
	Error(Day*Trial type)	33.804	15	2.254		

Table 13: Paired samples test on rapid response measures ("Repeat Group")

				95% CI of the difference				
	Mean	**Standard Deviation**	**Standard Error Mean**	**Lower**	**Upper**	**t**	**df**	**Sig (2-tailed)**
Reaction time day 1 (Repeats – NoRepeats)	-0.14166	0.05492	0.01373	-0.17093	-0.11240	-10.318	15	0.000
Reaction time day 5 (Repeats – NoRepeats)	-0.11513	0.05254	0.01313	-0.14313	-0.08714	-8.765	15	0.000
Improvement	-0.02875	0.03304	0.00826	-0.04636	-0.01114	-3.481	15	0.003
Errors* (Repeats – NoRepeats)	-5.85625	2.78639	0.69660	-7.34101	-4.37149	-8.407	15	0.000

*Errors = Average number of errors across day 1 and 5