Comparing backward chaining and mixed backward chaining in discrete motor learning

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Abstract

Practice regimes in motor learning strongly influence efficiency and quality of both acquisition and retention. This paper argues that by comparing backward chaining with mixed backward chaining, specific distinctions between the regimes could be visualized. Based on the Cognitive framework for Sequential Motor Behaviour (C-SMB), it was argued that backward chaining would show faster reaction times (RT) during the first testing phase, while the mixed backward chaining condition was hypothesized to perform better in the second testing phase. The experiment was conducted letting the participants (N=24) complete the discrete sequence production (DSP) task in two equal-sized groups. Upon completion, results showed the hypothesis to not be confirmed completely and rather suggested the mixed backward chaining to generally be a more effective approach. One explanation could be the similarity of regimes in practice, which might inhibit to observe strong differences. Future research could be centered around more distinctive approaches.

Keywords: motor sequence learning, discrete sequence production (DSP) task, backward chaining, mixed backward chaining, practice regime

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Motor Sequencing Skill and Learning

Every performed movement in our daily life consists of several individual movements. This ranges from fitness training to paying by card in a grocery store and is described in scientific literature as a motor sequence (Ruitenberg et al., 2012). The fluent performance of successive movements is termed motor sequencing skill (Abrahamse et al., 2013; Ghilardi et al., 2009). Each motor skill must at some point be acquired through motor (sequence) learning (Abrahamse et al., 2013; Magil & Anderson, 2016). Precisely, motor learning is divided into acquisition, referring to learning of novel motor sequences, and retention, which targets the application of the learned sequence (Jarus & Goverover, 1999; C. Schneider, 2021; Verwey et al., 2010, 2021). Both acquisition and retention performance can be enhanced through motor learning but differ in improvement depending on the practice regime (Herzog et al., 2022; Jarus & Goverover, 1999; Lee et al., 1991; Magill & Hall, 1990). With the first theoretical approaches being developed in the 1960s, the pursuit of the most efficient practice regime lasts over sixty years and still continues (Fontana et al., 2009; Hajian, 2019; Hossner et al., 2016; Naylor & Briggs, 1963; Verwey, 2001). One approach to pursue this is the discrete sequence production (DSP) task, which is also utilized in the present study.

Discrete Sequence Production Task

A discrete motor sequence describes a succession of individual movements, characterized by having a discrete beginning and ending (Fontana et al., 2009). In 2001, Verwey proposed the discrete sequence production task which utilizes keypresses for motor learning research (Verwey, 2001). The DSP task works by presenting a participant three to eight visual stimuli (squares) on a computer screen, each associated with one specific keypress(Verwey et al., 2014). The stimuli will light up one by one, indicating to the participant to press the corresponding key. Over the course of the experiment, every stimulus is presented the same number of times to counterbalance individual differences (Verwey et al., 2014). In the present study, DSP research is split into two different sessions. During the first one, the participant faces the training phase, where one of two practice regimes is applied to acquire the discrete motor sequence (Verwey et al., 2010). This is followed by a retention phase, which is the same for all participants and examines the acquired motor sequences (Abrahamse et al., 2013). After six to eight days, the participant completes the second session, which consists of the same retention phase as before (Wright et al., 2015). Response time (RT) and error rate are measured during all phases to track progress during training (Abrahamse et al., 2013; Verwey et al., 2010).

Cognitive framework for sequential motor behaviour

Research with the DSP task led to the development of the dual processor model (DPM), which was later extended to the cognitive framework for sequential motor behaviour (C-SMB). This framework introduced three different modes of learning and executing novel motor sequences, facilitated by two cooperating processors (Verwey, 2001; Verwey et al., 2014). In the reaction mode, a stimulus is received by the central processor, which then translates it into a motor response and transfers the information to the motor processor, which performs a physical reaction (Abrahamse et al., 2013). As each of those reactions is retrieved manually, this is a rather slow process in terms of temporal effort. In addition to the two processors, the C-SMB introduced the motor buffer, a fragment of the short-term memory (STM) which can store between three and five motor representations of physical reactions, allowing for faster execution as it circumvents the central processor (Abrahamse et al., 2013; Verwey & Abrahamse, 2012).

Persistent motor learning forms mental associations between singular reactions, which is then termed associative mode and accelerates performance, as it does not require separate response selection for each stimulus anymore (Verwey, 2015). With ongoing motor learning, these associations strengthen and form motor representations, called motor chunks, in the long-term memory (LTM; Abrahamse et al., 2013; Verwey & Abrahamse, 2012). Such chunks are loaded from LTM into motor buffer before and during execution, to ensure smooth performance (Abrahamse et al., 2013; Verwey, 2015). The associative mode then changes to chunking mode, during which only the first stimulus is necessary to trigger the associated motor sequence, stored in the chunk (Abrahamse et al., 2013; Krakauer et al., 2019; Verwey et al., 2014). Practically, this can be compared to the observed development of rhythm while acquiring a motor skill, creating a flow during execution (Passingham & Sakai, 2004; Sakai et al., 2004).

During both training and resting phases, dynamically changing activation in different brain areas could be observed in behavioral, electrophysiological, fMRI and cellular methods (Luft & Buitrago, 2005). Results are in line with other findings suggesting that motor learning takes place in the areas cortex-basal ganglia and cortex-cerebellum (Hikosaka et al., 2002), with the latter also being responsible for aforementioned rhythm (Sakai et al., 2004). Due to the formation of specialized neuronal circuits (Wiestler & Diedrichsen, 2013), chunking in skill learning leads to less demanding encoding (Bor et al., 2003) and increased performance (Bor et al., 2003; Sakai et al., 2004) The suggested superiority of chunking to its two preceding modes now raises the question how training must be scheduled to achieve this mode most efficiently. To find an answer to that question, different practice regimes will be discussed.

Practice regimes

DPM and C-SMB illustrate the mental processes of motor learning and confirm its general positive effect on acquisition and retention (Abrahamse et al., 2013; Bor et al., 2003; Verwey & Abrahamse, 2012) but these models are not designed to conclude on the effectiveness of different practice regimes. According to Naylor and Briggs' (1963) hypothesis, motor learning can be divided into whole practice (WP) and part practice (PP) methods. The difference in effectiveness of practice regimes is hypothesized to originate in a tasks level of complexity and organization, specifically the degree of interdependence of successive movements (Naylor & Briggs, 1963). During WP, the motor sequence is repeated as a whole in both practice and testing blocks, which appeared useful for tasks with high organizational demand and low complexity (Moore & Quintero, 2019; Naylor & Briggs, 1963). In PP, the motor sequence is split into several units of individual movements, which are learned isolated from one another and assembled to a sequence in the testing block (Fontana et al., 2009; Naylor & Briggs, 1963). Here, benefits are expected for tasks with high complexity and low organization, as singular individual movements are learned extensively due to their high complexity and assembled more easily afterwards due to their low organizational demand (Ash & Holding, 1990; Fontana et al., 2009; Naylor & Briggs, 1963). Further, research shows that PP improves both encoding during acquisition phases and performance during the retention phase (Bor et al., 2003; Wiestler & Diedrichsen, 2013). It can be concluded that a distinction of learning methods into WP and PP can already influence learning progress. This raises the question what practice regime might be most favorable for DSP task application.

Forward vs backward chaining

The examination of whole and part practice leads to investigate whether other learning regimes could improve effects in acquisition and retention. This was approached by dividing PP methods in forward chaining and backward chaining (Moore & Quintero, 2019; Smith, 1999). Forward chaining is done by practicing the first unit of a task first, then the first followed by the second etcetera (A – AB – ABC), which then creates a forward running chain. During backward chaining the distribution is the same, but the order is the opposite way, practicing the last unit first, followed by the last and the middle one, etcetera (C – BC – ABC) (Kim et al., 2018; C. Schneider, 2021; Smith, 1999).

As explained by the C-SMB, motor learning repetition causes associations between motor responses followed by chunking (Abrahamse et al., 2013). In forward chaining, an already chunked part is always followed by a part which requires individual responses to each stimulus and would therefore be approached in the slower reaction mode (Verwey, 2015; Verwey & Abrahamse, 2012). Backward chaining follows the same rhythm in opposite direction when moving from reaction mode to association and then chunking for the respective blocks, which allows for the assumption that both methods would require the same amount of time (Verwey et al., 2014; Verwey & Abrahamse, 2012). Previous research show that chunking leads to the formation of neural networks, facilitating a faster response execution (Hikosaka et al., 2002; Passingham & Sakai, 2004). Based on work by Wilcox (1974), concluding that backward chaining leads to faster chunking and work by Bor (2003), stating that chunking leads to faster encoding, backward chaining could be concluded to be the faster learning method in comparison to forward chaining. This is in line with the variability of training hypothesis, stating that increased variability instead of linear training facilitates a more rapid acquisition process (Pesce et al., 2016; Wrisberg & Ragsdale, 2013). Applied to the DSP task however, this appears to be questionable as a recent study by Schneider suggested WP to be superior to PP, based on the length of the respective sequences (2021). So, while backward chaining provides the possibility to make learning a sequence more adaptable without tying it to a specific order in which the sequence is tested afterwards, it is still not clear whether it proves more effective in this specific field of application.

Random vs blocked practice

As backward chaining already benefits from less context-dependent learning, researchers strived to maximize this effect in random practice (RP). In accordance with the presented line of evidence, a multitude of studies reported the RP group to outperform the BP group during retention, despite inferior performance during acquisition phases (Herzog et al., 2022; Kim et al., 2016, 2018; Lin et al., 2018; Verwey et al., 2010). Dang and colleagues (2019) proposed the reason for this to be a stronger detachment of acquired material from respective context, placing more emphasis on the stimulus responses. This is in accordance with findings from Verwey (2021), indicating that, during RP, the presented unit is loaded to the motor buffer during each trial. The disconnect of learned material and its respective context is also known as contextual interference (CI) effect (Dang et al., 2019; Kim et al., 2018; Sekiya, 2006; Verwey et al., 2021). This leads to improved consolidation during resting periods (Lin et al., 2018; Thürer et al., 2019), which explains the improved retention as opposed to mediocre acquisition phase performance. In DSP tasks, random practice was for example designed with 4 blocks of 4-6 stimuli which are practiced in random order but afterwards tested in the same testing block as the control condition (Kim et al., 2018; Lin et al., 2018). In the present case, it was investigated whether random as opposed to blocked practice shows better results in the final testing. due to less contextual interference, or a better performance, due to improved chunking.

The present study

Based on the presented line of evidence, it was fair to assume that backward chaining would be an effective learning method for motor learning using the DSP task. A study by C. Schneider (2021), however, showed this to be questionable, as it demonstrated WP to be significantly more effective than backward chaining for the DSP task using nine-keypress-sequences. Naylor and Briggs' (1963) hypothesis claims, that this was due to insufficient complexity in the sequence length, resulting in WP being the more effective method. The current practice regime was therefore altered to follow a 15-key-sequence, split into three 5-keypress-sequences. The backward chaining group followed a regular backward chaining regime, while the mixed backward chaining group randomly faced five-, ten- or fifteen-keypress-sequences during the acquisition phase. This was expected to have an effect similar or comparable to random practice, as it moves away from a strict order-related approach. The backward chaining group was expected to show more effective learning and retention in the first testing phase, leading to a lower error rate and RT compared to the other group (Ash & Holding, 1990; Bor et al., 2003; Smith, 1999; Wilcox, 1974) Comparing the two groups and taking into consideration discussed research, average RT was expected to be lower for the mixed backward chaining group during the second testing phase a week later, due to improved consolidation (Herzog et al., 2022; Kim et al., 2016; Lin et al., 2018).

Methods

Participants

After ethical approval by the University of Twente, the participant recruitment started via the university-internal SONA system, as well as face-to-face marketing. In total, 24 participants, consisting of University of Twente students as well as external participants, were recruited. All of them adhered to the participation criteria of being right-handed, not at risk for nicotine withdrawal symptoms, within the age range of 18-35 and sober for at least 24 hours. Precisely, nine male and 15 female participants (*M*=20.7 years, *SD*= 2.56 years) from a variety of countries were randomly assigned to either the Backward Chaining (BWC) or the Mixed Backward Chaining (MBWC) condition. Before starting the experiment, each participant was instructed about their rights and signed a physical informed consent form (see Appendix A).

Apparatus

The study took place exclusively in the Laboratory for Behavioural, Management and Social Sciences (BMS Lab) of the University of Twente. Each room consisted of a desk with a Dell OptiPlex 7050 PC as well as a chair and a window with 75% closed curtains, which served as the sole source of ambient lighting. A GoPro camera was mounted above the window to allow for the observation of the participant by the researchers, while none of the videographic data was actually stored. The computer was running on Windows 10 and presented the DSP task on a 24-inch AOC G2460PF LCD Monitor (144Hz) in a 1920x1080 resolution. To operate the system, a 4World PN:07319 (QWERTY) keyboard with a PS/2 connection and a Dell MS116t mouse were provided. The DSP task was programmed in E-prime, which both presented stimuli and recorded responses and was ensured to be the only program running in order to avoid unnecessary usage of random-access memory (RAM). Before entering the experiment room, participants were asked to leave all possible distractions (smartphone, smartwatch, backpacks) in the entrance area with the researcher. Finally, the participant was placed on the chair with an approximate 50-60cm distance to the screen.

Materials

Demographics (age, gender, nationality) were derived from a Qualtrics questionnaire, filled in by the participants upon sign-up in the SONA system. Additionally, for external participants or those who were signed up manually, age and gender were collected in a brief questionnaire towards the end of the experiment. Each of the participants was given oral information about structure, content and purpose of the study, as well as withdrawal criteria.

Experimental stages

First session

For the task, four black square outlines were presented in horizontal order in the center of a white screen. These represented the 4 stimuli, of which one at a time lit up in bright green. Each of the four stimuli was associated with the one of the keys “C”, “V”, “B”, “N” on the keyboard in the same order. Thus, the square on the very left was associated with “C”, the one next to it with “V”, etc etera. Further, each of the keys was associated with one specific finger, with the outer keys “C” and “N” being associated with the left and the right middle finger and the two inner keys “V” and “B” being associated with the left and right index finger. Ultimately, this led to one specific stimulus triggering one finger to press the corresponding key.

Starting the experiment, the first stimulus was presented after a random waiting period between 500 and 2500ms. If a participant pressed a key which did not match the corresponding stimuli during the trial, an error message occurred on the screen. Same happened for premature keypresses. After each block, participants received feedback on the number of errors, response time and performance. Further, they had a one-minute break after which the researcher entered the room and manually started the following block. After the last block, the participants were not required to wait and could leave the trial room on their own.

Participants in the backward chaining condition followed an acquisition protocol, which, during the first block, asked for one of the five-keypress sequence variants “N-V-C-B-V”, “B-C-N-V-C”, “V-N-B-C-N” or “B-C-N-V-C”. Based on those, the second block demanded a ten-keypress-sequence, of which the last five were identical to the respective previous sequence. An example for this is “C-B-V-N-B-**N-V-C-B-V**”, which presents the novel sequence “C-B-V-N-B” prior to the already acquired “N-V-C-B-V”. The third block of the acquisition phase continued in similar fashion, again presenting a novel five-keypress-sequence before the already learned ten-keypress sequence. For instance, the aforementioned example was extended to “V-N-B-C-N-**C-B-V-N-B-N-V-C-B-V**”, adding “V-N-B-C-N” on top of the already acquired ten-keypress-sequence. Each of these blocks was repeated twelve times which accumulates to 60 keypresses for the first, 120 for the second and 180 for the third block. This was followed by a testing block, which consisted of the 15-keypress-sequence to be repeated 7 times, accumulating to further 105 keypresses and concluding the first session of the experiment.

For the mixed backward chaining condition, the acquisition protocol showed the same sequences but structured differently. In the first four repetitions of the first block, the condition demanded a five-keypress sequence such as “V-N-B-C-N”. The following four repetitions were “B-C-N-V-C-**V-N-B-C-N**” and the last four repetitions “N-V-C-B-V-**B-C-N-V-C-V-N-B-C-N”**. Then, the first block was over. A total of twelve repetitions, split into four for each sequence accumulates to 120 counterbalanced keypresses in total for the first block. As the second and third block are executed following the same regime, this acquisition protocol also demands a total of 360 keypresses. The testing block was seven repetitions of the 15-keypress-sequence to conclude the session again.

Second session

The second session was conducted 6 to 8 days after the first one and followed the same protocol across both conditions. The fifth block of the DSP task consisted of the same 15-keypress-sequence which the participant had entered in the fourth block in the prior session. This time, it was repeated 20 instead of seven times, which led to a total of 300 keypresses.

Afterwards, participants completed an awareness test. For this, the keyboard was covered and only the mouse was used to click on the stimuli. Participants were informed orally and via on-screen information that they would first have to put in a 15-mousepress-sequence themselves and repeat it afterwards without any indication of their input. Further, they were informed that they could guess the stimuli if they did not remember them. The stimuli were presented horizontally in the middle of the screen for the first indication-repetition passage and afterwards presented in a diamond shape with the same instructions. Lastly, participants were asked to answer three questions by clicking on the screen and enter their age. This concluded the second session.

Analysis

For each keypress, as well as the mouse presses during the awareness task, the response time was measured. This was defined as the time passed between the display of the stimulus and the corresponding keypress. In addition, the error rate was derived from the number of incorrect keypresses during each block and transformed to arcsine proportions to utilize in the analysis. It was investigated what differences the practice regimes showed on response time and error rate, for both sessions. Blocks one, two and three (acquisition phase) were excluded from the analyses, as they differed across the two conditions and therefore did not offer comparable results. Two analyses were conducted. The first one examined the influence of the regime on RT, where Key, Block and Condition served as independent variables, with RT being the dependent one. During the second analysis, error rate was the dependent variable, while the independent variables Block and Condition remained identical and Key was not considered. Based on this, the learning progress (reduction of independent variables) was analyzed.

Results

Testing for the assumption of sphericity did not apply in the present case, as the Mauchy-Test of sphericity was significant. Abbreviations used in the following paragraphs are standard error (SE) and standard deviation (SD).

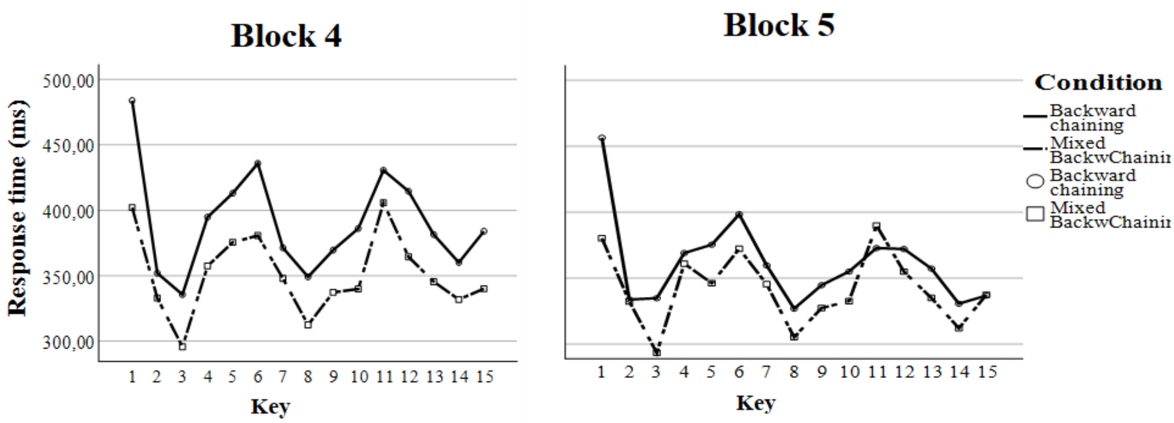
Response time

A 2 (Practice regime: BWC vs MBWCx 2 (Block 4 vs 5) x 15 (Keys) repeated measures ANOVA was used, analyzing between-subject variable Condition and within-subject variables Block and Key.

The main effect of Block was significant, $F(1,22)=4.55$, $p=0.044$, $\eta_p^2= 0{,}172$. The interaction between Condition and Block however was not significant $F(1,22)=1.156$, $p=0.294$, $\eta_p^2=0{,}05$, as was the main effect of Condition $F(1,22)=3.69$, $p=0.068$, $\eta_p^2=0{,}144$. The mean RT in the BWC condition improved from 390.8ms (Block 4, *SE*=13) to 361.5ms (Block 5, *SE*= 12.4). For the MBWC condition, respective values also lowered from 351.3ms (Block 4, *SE*=13) to 341.6ms (Block 5, *SE*= 12.4). In total, RT reduced from 371ms (Block 4, SE=9.2) to 351.6ms (Block 5, *SE*=8.7).

Figure 1:

Mean Response Time Across Both Blocks And Conditions



The main effect of Key was statistically significant $F(14, 308)=13.578$, $p=<0.001$, $\eta_p^2= 0{,}382$. While the interactions of Key and Condition, $F(14, 308)=1.014$, $p=0{,}438$, $\eta_p^2=0{,}044$, and Key and Block $F(14, 308)=0.846$, $p=0.619$, $\eta_p^2=0{,}037$, were not significant, respective Key RT did offer insights in response patterns. In Block 4 of the BWC condition, Keys 3 (335.6ms, *SE*=13.3), 2 (351.9ms, *SE*=12.1) and 8 (349.1ms, *SE*=13.5) were pressed the fastest. In Block 5, this changed to Key 8 (326.8ms, *SE*=12), 14 (330.6ms, *SE*=14,9) and 2 (333.7ms, *SE*=16,5). In both Blocks, Keys 1 (Block 4: 483.8ms, *SE*=32.3; Block 5: 456.4ms, *SE*=23,9), 6 (Block4: 435.8ms, SE=20; Block 5: 398.4ms, *SE*=23.9) and 11 (Block 4: 430.5ms, *SE*=25.6; Block 5: 372.7ms, *SE*=17.3) showed the highest RTs. Interestingly, along with the highest response times, these keys also consistently show the highest standard error.

For the MBWC condition, during Block 4 Keys 3 (295.7ms, *SE*=13.3) and 8 (312.4ms, *SE*=13.5) and 14 (331.8ms, *SE*=18.4) had the lowest RTs, which repeated during Block 5 (Key 3: 293.3ms, *SE*=23.9; Key 8: 305.2ms, *SE*=12; Key 14: 334.9ms, *SE*=17.2). The highest RTs showed the same pattern as in the BWC condition during both Block 4 (Key 1: 402ms, *SE*=32.3; Key 6: 380.7ms, *SE*=20; Key 11: 405.7ms, *SE*=25.6) and 5 (Key 1: 380.2ms, *SE*=23.9; Key 6: 372.2ms, *SE*=23.9; Key 11: 389.8ms, *SE*=17.3), with the slowest being 1, 6 and 11. Again, those represented the higher end of the standard errors as well.

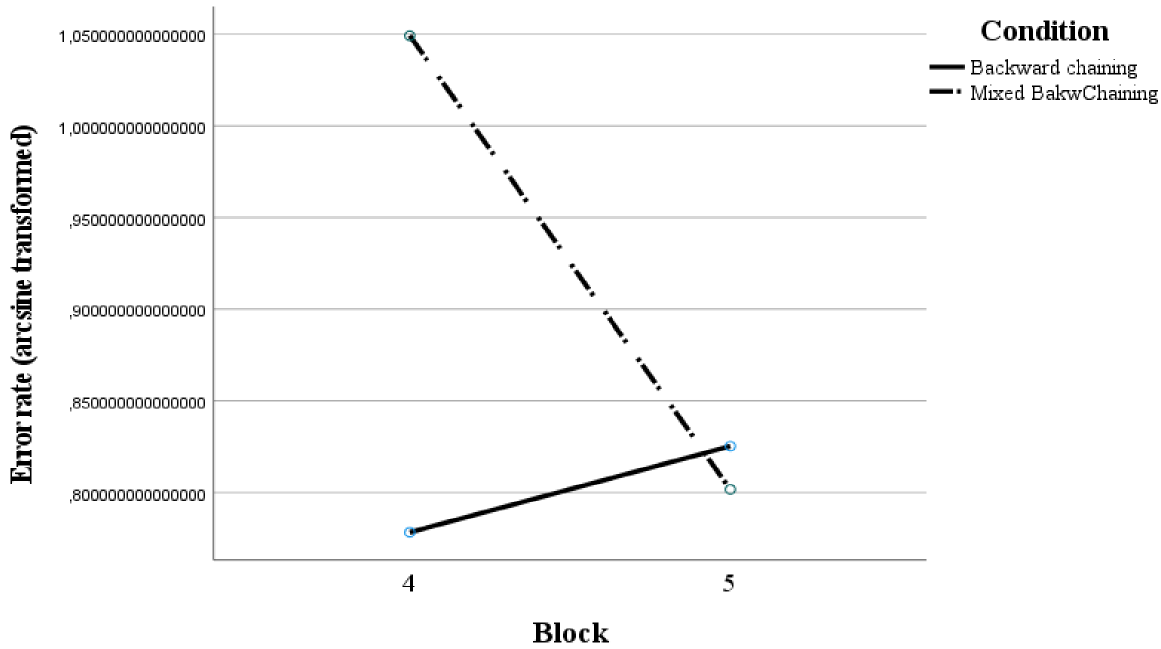
Error rate

A 2 (Practice regime: BWC vs MBWC) x 2 (Block 4 vs 5) ANOVA was used to analyze the arcsine transformed error rates. In this mixed design, Condition (practice group) served as the between-subjects variable, while the training Block was the within-groups variable.

The main effect of Condition showed to be not significant $F(1,22)=1.159$, $p=0.293$, $\eta_p^2=0{,}05$, as it was for Block $F(1,22)=1.497$, $p=0.234$, $\eta_p^2=0{,}064$. The mean error rate of the BWC condition developed from 0.778 (*SD*=0.263) during Block 4 to 0.825 (*SD*=0.342) during Block 5. The MBWC mean error rate of 1.049 (*SD*=0.308) in Block 4 improved to 0.802 (*SD*=0.444) in Block 5 (see Figure 4). Overall, mean error rate across groups reduced from 0.914 (Block 4, *SD*=0.312) to 0.814 (Block 5, *SD*=0387).

Figure 4:

Mean error rates for both conditions, across both Block 4 and 5



Discussion

This study investigated the practice regimes backward chaining and mixed backward chaining in a DSP task setting, aiming to find the more effective method. In the present experiment, participants were randomly presented one of the regimes for learning 5 to 15-keypress-sequences, followed by a 15-keypress testing phase (Block 4), which was repeated a week later (Block 5). Based on an extensive literature review, participants in the backward chaining condition were expected to perform better in the first testing phase, while mixed backward chaining was expected to yield better results after the 6-8 days consolidation phase. Results can only partially confirm this, as backward chaining participants did not show superior performance during Block 4. During Block 5 however, the mixed backward chaining group showed lower RTs than its counterpart, which illustrates the expected improvement after a consolidation phase (see Figure 1).

Generally, it may be concluded that during this DSP task experiment, the consolidation phase played a larger role than the respective practice regime. Both groups improved their means from the 4^{th} to the 5^{th} block, but backward chaining showed longer mean RTs than mixed backward chaining for both blocks. This suggests that both conditions benefit from the consolidation phase, but not necessarily from their respective regimes, which is in line with the significant main effect of Block, opposing the insignificant effect of Condition. In search for an explanation, these findings lead back to the C-SMB. Repetition facilitates performance, by associating and chunking related stimuli (Abrahamse et al., 2013; Verwey & Abrahamse, 2012). This also happens on neural pathways, where adaptation to frequency facilitates retention (Bor et al., 2003; Passingham & Sakai, 2004; Wiestler & Diedrichsen, 2013), which explains why the RTs improved similarly. Thus, differences in present practice regimes might not be as large as expected and only account for the difference in respective chunking.

Expectations that the mixed backward chaining group would benefit more from the consolidation phase could not be confirmed, as they improved less from Block 4 to 5 than the backward chaining group. There was a trend in the error rates indicating a strong decrease from Block 4 to 5 for mixed backward chaining and a slight increase by the other (see Figure 4). With the only structural difference between the two conditions being the sequence of stimuli, the variability of training hypothesis seems apparent, as adding variation to otherwise repetitive learning is known to improve acquisition and retention (Pesce et al., 2016; Wrisberg & Ragsdale, 2013). For the more straightforward backward chaining condition, the RTs suggest an improved chunking, especially around the keys 6 and 11 which to that extent cannot be observed for mixed backward chaining.

The patterns of the RT offer further interesting insights. Across both conditions, the slowest keypresses on were key 1, 6 and 11. With the task containing one to three 5-keypress-sequences, those three keys represent a concatenation point, from which on the following 4 keypresses are happening significantly more rapid (Abrahamse et al., 2013; Verwey, 2015). In recent publications, researchers suggested a 9-keypress-sequence to be too short to make use of this, which the current research design seems to have improved (C. Schneider, 2021; V. Schneider, 2021). That fact that the main effect of Key for RTs is significant, while it is not for the error rates, can be understood as the number of the key only having influence on its RT, not on whether or not it was pressed correctly.

Limitations

As in the present case, the difference between conditions is fairly small, more distinctive numbers could probably have been observed with practice regimes which more clearly differ between each other. In DSP tasks, the complexity of singular keypresses seems rather low and the emphasis is on the correct order of the keypresses after one another, which would make whole practice the better fit, according to Naylor and Briggs' hypothesis (1963). This is in line with findings from other publications (C. Schneider, 2021), for this specific application. One approach could be a whole practice alternative to one of the two rather similar backward chaining variations, which could have achieved more distinct results and significant findings.

Another limitation of the present research is its generalizability. The DSP task is a rather specific activity and only shows similarities to tasks in the realm of motor sequences. Insofar, it remains open whether findings could be applied to general teaching approaches. If that was the case, the present study would make it hard to decide between backward chaining and mixed backward chaining, as the results only differ in nuances and translating that to real-world application would be difficult.

Lastly, the sample was mostly derived from convenience sampling in and around the university. This makes it W.E.I.R.D., an acronym for the terms Western, educated, industrial, rich and democratic (Dan, 2010). Consequently, the results are generalizable to people of the same categorization, at best. While the compartments of the acronym are not necessarily connotated negatively, they do suggest the exclusivity of study results. In pursuit of more universal or generalizable results, striving for more diverse samples would be reasonable.

Future research

As briefly discussed before, the two conditions did not differ substantially, mainly because one is a variation of the other, but still show differences in development for the participant. Backward chaining emphasizes chunking and especially in less organization-dependent settings, is likely to be applicable. The strength of this method could especially be observed in the improvement of RTs from Block 4 to Block 5 (see Figure 1). With mixed backward chaining or alternatives which make use of the contextual interference effect, a different kind of learning seems to emerge. Here, the skill itself, improving RT to a stimulus, is central. This is shown in the error rates, which decline drastically comparing Block 4 and 5 (see Figure 4).

For future designs, it could be valuable to capitalize on regime differences and try maximizing the effect, in DSP task settings. Instead of backwards chaining, a variation of whole practice could be used, as it is more fitting to the nature of the exercise. As an alternative to mixed backward chaining, differential learning could be interesting. Emerging from sports science on the basis of biomechanical patterns (Schöllhorn, 2016), it has not been represented in DSP research so far. While contextual interference utilizes randomness in a fixed setting, this approach suggests a self-guided system with gradually adjusted difficulty (Schöllhorn et al., 2022). Specifically, Schöllhorn and colleagues suggest changes such as bigger and smaller stimuli, acoustic distortion or different brightness of the screen to provoke mistakes and the need to develop a coping mechanism. Thus, we recommend comparing whole practice to optimize chunking, and additionally a differential method to optimize mere stimulus-response. With this, a larger distinction between two different learning models would potentially be achieved.

Conclusion

In conclusion, the first hypothesis, namely that the backward chaining condition would outperform the mixed backward chaining condition in the first testing phase, could not be confirmed. The second hypothesis, mixed backward chaining outperforming backward chaining in the second testing phase, could be confirmed. Nevertheless, these results cannot be said to reflect the effectiveness of mixed backward chaining compared to backward chaining with complete certainty, as the mixed backward chaining condition provided shorter RT during both testing phases and no distinct development between the phases could be observed. Most of the statistical main effects were shown to be not significant. Despite this, the main effect of the variable Key was significant, which can be explained by the observed pattern of the RT and suggests that the practice regimes successfully triggered chunking within the participants. In future research, it is recommended to choose practice regimes with clearer distinctions between each other to increase observable difference and comparability. Still, the findings of this study show that chunking constitutes a large part of the learning progress, although the generalizability of the findings is debatable.

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Appendix A

Informed consent form

Consent Form for Investigation into the Learning of Discrete Movements

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
I understand that taking part in the study involves me pressing a series of keyboard keys. While doing so, my response time and error rate will be recorded by the computer. First, there will be a part for learning the sequences (about 120 keypresses), after which my performance will be measured in a test.	☐	☐
I agree to hand my phone to the researcher so that I will not be distracted. The researcher will not do anything with it besides keeping it safe.	☐	☐
Risks associated with participating in the study		
I understand that taking part in the study is not associated with any risks. However, if any complaints emerge I can contact the researcher anytime and know how to.	☐	☐
Use of the information in the study		
I understand that information I provide will be used for a student's bachelor thesis. It will be anonymized and no individual results will be found in the report.	☐	☐
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	☐	☐
Future use and reuse of the information by others		
I give permission for the deindividualized data that I provide to be archived on safe University of Twente server so it can be used for future research and learning.	☐	☐

Signatures

____________________	____________________	________
Name of participant	Signature	Date

I have accurately read out the information sheet to the potential participant and, to the best of my

______________________ ______________________ ________

Researcher name Signature Date

Study contact details for further information:
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Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-bms@utwente.nl