The Serial Reaction Time Task: Improved Implicit Motor-Sequence Learning Detection

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Abstract

Implicit motor skill learning consists of various pathways, to which interconnecting regions in the *Basal Ganglia* and the *Cerebellum* play an essential role. Occurring in two sets of loop circuits as cortex-basal ganglia and cortex-cerebellum, they account for spatial-associative and motor learning, processes that are deteriorated in various neurodegenerative diseases. The Serial Reaction Time Task (SRTT) is an often used tool to detect implicit motor learning measurement. The aim of this project is to improve the SRTT to provide more accurate insight in motor learning processes of individuals by adapting to their learning needs. The improved SRTT was tested in a pilot study consisting of sixteen healthy right-handed participants for the conditions action, goal and different sequence. Results showed that with the developed SRTT participants did not perform implicit motor skill learning but also that they were not biased to better performance of neither cerebellar nor basal ganglia based testing. In future, advanced individually adapted SRTT's could help improving Alzheimer's diagnosis.

Summary

Motor skills are acquired either explicitly, this is through conscious work to remember the movement, or implicitly, which is a subconscious and effortless memorization. Implicit motor learning of a sequence is taking place in interconnection brain regions of the *Cerebellum* and the *Basal Ganglia*. We are interested in measuring implicit learning because in neurodegenerative diseases such as Alzheimer's disease, implicit learning processes are deteriorated. A tool to measure implicit motor-sequence learning is the Serial Reaction Time Task (SRTT), a reaction time test containing a repeating sequence. In this project it is our aim to improve the SRTT so that we can measure implicit motor learning adapted to each participant's individual learning requirements. To do this, we tested sixteen healthy participants in a pilot study with our improved SRTT. We expected them to have a high learning quote, however, results showed that with this SRTT participants did not perform implicit motor learning. We also found that participants did not perform better on neither *Cerebellum* nor *Basal Ganglia* based tests, thus do not have an inclination to either one of them that would alter the test interpretation. Future studies will focus on ameliorating the individualized SRTT to give evidence for the extent of neurodegenerative processes.

1 Introduction

1.1 Implicit Motor Skill Learning Tests

Human motor skill learning involves the acquisition, processing and interpretation of experienced information. As Vernon B. Brooks [1] observed in 1986, however, humans do not learn motor skills as a whole. Rather, they make a distinction between the target results and the specified parameters of the movement, in principle a differentiation between the goal and the movement component. An example for movement execution with this differentiation is when a pianist learns a piano sonata: In a goal-based learning process, the pianist is required to select the piano keys according to the chords. Once this is achieved, he needs great motor skill to move his fingers appropriately to produce the desired melody [2].

Based on these separate features of motor skill learning, O. Hikosaka, K. Nakamura, K. Sakai and H. Nakahara [3] proposed in 2002 two independent sets of regulating loop circuits located in different areas of the brain: the cortex-basal ganglia loop, which regulates movement-based learning, and the cortex-cerebellum loop, which regulates goal-based learning.[1] Supporting Hikosaka's thesis, it has been observed that patients with deteriorated Basal Ganglia[2] perform worse on movement-based motor skill tests than healthy test subjects [4].

This kind of non-intentional, so called *Implicit learning* takes place in a passive, incidental and automatic learning process of a motor sequence. No conscious effort to acquire the skill is required. Contrarily, explicit learning requires deliberate consciousness and active memorization of content [5]. However, implicit motor learning tests are encountering a number of obstacles in their procedure.

An ideal implicit learning test must provide equal testing conditions for all groups of testing subjects, thus operates age-independently, does not depend on an IQ score and does not favor neurologically fitter subjects [6]. The test needs to filter out, collect and display sensitively only what has been learned throughout the course of the experiment. In addition to this, implicit learning tests must act under a certain time pressure because once time elapsed after the test, the subject's memory sets in and builds in a process of explicit learning connections. [7]

An implicit motor learning test enough sensitive to consider all these aspects would allow more accurate documentation of motor skill improvement. Therefore, this project aims on answering this fundamental problem:

[1] View 1.2 The Central Mechanisms of Motor Skill Learning

[2] Most common diseases resulting from Basal Ganglia deterioration are Parkinson's disease and Huntington's disease.

How can we develop a method to measure motor skill improvement individually tailored to each test subject?

To do this, we modify a Serial Reaction Time Task[3] (SRTT) to adapt testing to all participants' individual motor skill learning.

Wider knowledge about evolution and function of distinct brain areas obtained with such tests can be used to develop early detection techniques for neurological disorders. By understanding interactions between the different regions of the brain, we can improve diagnoses and treatments.

1.2 The Central Mechanisms of Motor Skill Learning

Although initially regarded as simple behaviors, motor skills are now understood to be extraordinarily complex. It has turned out that it is impossible to explain them solely with synaptic plasticity[4] in single neurons. According to the results of recent integrative approaches, interactions between multiple neural networks, such as the various motor cortices[5] and the prefrontal parietal cortex[6], are dynamic [3]. These diverse features have prompted several neural theories about the processes of motor learning. Hikosaka et al. [3] proposed in 2002 a widely approved method of the interaction between the prefrontal parietal cortex and the motor cortex by laying emphasis on the Basal Ganglia (BG) and the Cerebellum (CB):

These two brain structures "influence the processing of motor control and modulate the output of the descending pathways without directly causing motor output." [9] Hence as they both affect the interpretation of motor learning but do not control it, Hikosaka named them *side loops* to their afferents. As illustrated in Figure 1, a motor sequence is always represented in two ways: as spatial and as motor sequence[7]. Exemplarily, the sequence is first processed in the prefrontal parietal cortex as a spatial sequence. There, a loop circuit with the associative regions of the BG and the CB is formed. Once the sequence is acquired spatially, it is converted into a motor sequence, a process called spatiomotor conversion. This conversion is taking place in the motor cortex, which forms a loop circuit with the motor regions of the BG and the CB. In the BG, signals are assessed by their reward or their likelihood value, whereas in the CB,

[3] View 2.1 The Serial Reaction Time Task

[4] Synaptic plasticity: The ability of synapses to react on changes in their activity by growing stronger or weaker [8].

[5] Brain regions modulating movement.

[6] The prefrontal parietal cortex is also called association cortex, thus the brain region accounting for association-making.

[7] In the example of 1.1, the motor sequence is the order in which the pianist moves his fingers by following the spatial sequence, which is the goal of the pianist to produce the melody by playing the corresponding piano keys.

the sensorimotor or timing errors are controlled. Consequently, it is possible to independently optimize the performance of the spatial and motor sequence mechanisms. However, this gives rise to the inevitable event that spatial and motor mechanisms independently produce different results, called between-network error. In that case, the presupplementary motor area (pre-SMA) serves as "conflict monitor" between these networks.[8]

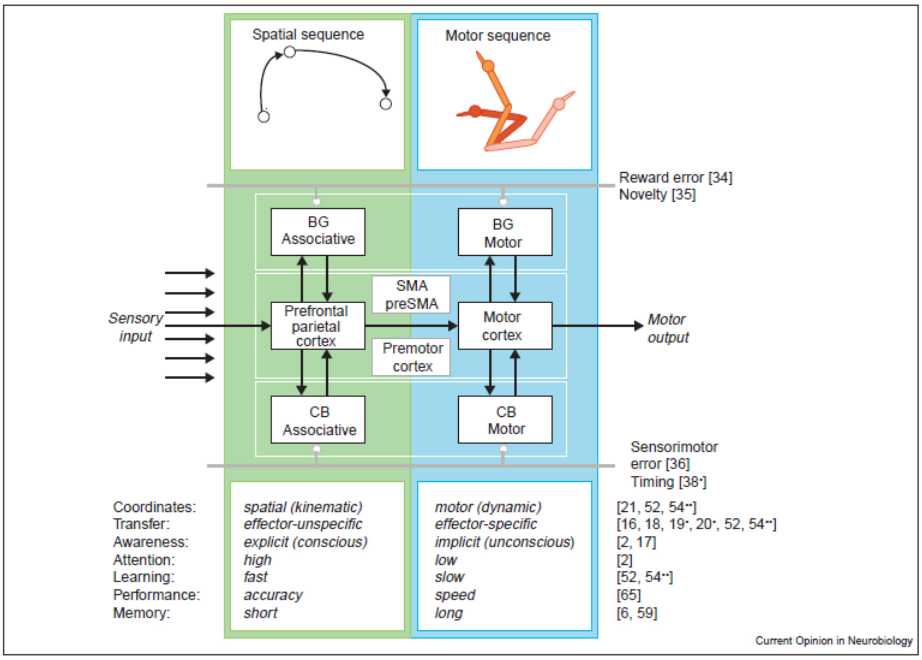

Figure 1: Scheme of motor skill learning based on two independent cortico-BG and cortico-CB loop circuits. (Okihide Hikosaka et al. 2002) [3]

The spatiomotor conversion process consists of various factors that influence the learning process, e.g. effector dependence: Spatial sequences are effector-independent (goal-based), whereas motor sequences are effector-dependent (movement-based). Reaching for a target, for example, keeps essentially the same goal, regardless of the effector represented by the target. Motor sequences, however, require differentiated muscle coordination based on the effector, thus are altered depending on the target. Furthermore, spatial sequences, e.g. reaching for a target, are acquired and processed quickly, but require ample attention. In contrast, motor sequences, e.g. performing the muscle coordination to reach for the target, are acquired slowly but require only minimal attention due to their subconscious regulation.

This model successfully accounts for various experimental observations, including the spa-

[8]The Supplementary and Presupplementary Motor Area (SMA and pre-SMA) are regions within the medial frontal cortex, that account for voluntary movement control. When there is a conflict in between responses, such as in an interference of implicit and thus subconscious motor- and spatial-based learning processes, the pre-SMA exerts control over the situation in terms of voluntary action. [10]

tiomotor conversion in the hand-transfer-task[9] conducted in this project.

2 Methods

2.1 The Serial Reaction Time Task

In this study, a Serial Reaction Time Task (SRTT) is used to investigate differences in spatial goal-based and movement-based learning. It consists of a classic hand-transfer-task[10] and has grown to become an approved tool to measure implicit motor skill learning - the incidental subconscious acquisition of motor skill. The SRTT was initially introduced by Nissen and Bullemer [11] in 1987 as a tool used for awareness tests in psychology.

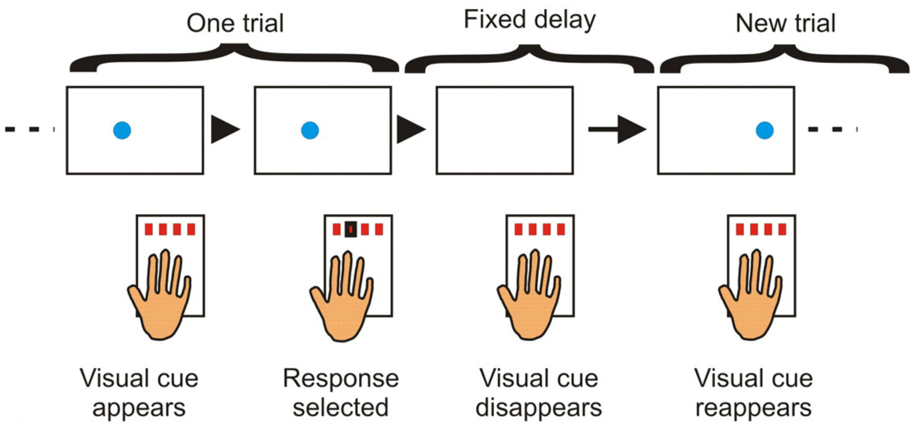

Figure 2: "A schematic of the SRTT: a visual cue appears, a participant responds by selecting the appropriate response button, the visual cue disappears, ending the trial, and after a fixed delay, another visual cue appears marking the beginning of a new trial. The position of the visual cue can either play out a repeating sequence or be random." (E. M. Robertson, 2007) [12]

In the SRTT, a visual cue can appear at one of four horizontally arranged positions on a screen. Each screen position, designated 1-4, is assigned to a button on a response box [13]. At the start of a trial, a cue appears and the participant has to select the appropriate response button, which ends the trial (Fig. 2). The duration of each trial, defined by the test participant's reaction time, is the primary task measure. At the end of each trial follows a short fixed delay, before another cue is presented.[11] Unbeknownst to the participant, the visual cues play out a repeating sequence of positions [12]. For instance, the original sequence by Nissen and Bullemer, the so-

[9]View 1.2 The Central Mechanisms of Motor Skill Learning

[10]Hand-transfer-tasks or intermanual transfer tasks are motor tests that investigate the skill transfer of a skill acquired with the one hand tested on the other.

[11]This fixed delay usually lasts about 200-500 ms. It is considered as not noticeable, yet inevitable accessory for visual processing. [12]

called N & B sequence, is 4-2-3-1-3-2-4-3-2-1. The presented visual cue moves from position 4 to 2 to 3 etc. Beginning and end of the sequence are not denoted by any means, so the end of the sequence cycles directly back to the beginning [14]. Through this process, participants subconsciously acquire the repeating sequence and become capable of predicting the pattern. After a fixed number of cycles, the visual cues are presented in a new, random order that does no longer play out a repeating pattern of positions [12].

To measure acquired skill, the SRTT contrasts the participant's reaction time for the sequential trials to his reaction time for the random trials. The reaction time is measured from the moment the visual cue is presented until the participant presses the correct answer key. Optimally, the participant's reaction time reduces gradually over the course of the task as the skill is subconsciously learned. The advantage of using the difference between sequential and random reaction time over using sequential reaction time alone is that when the sequence is unexpectedly removed and replaced with random trials, the participant initially continues to play out the sequence wrong. This mistake inflates the random reaction time, thus increases the difference between the sequential and random reaction time. In addition, it minimizes the effects of influential factors such as fatigue and shrinking motivation. Hence, the difference between sequential and random reaction time provides a specific and sensitive measure of skill acquisition in the SRTT [12].

The serial regularity of the SRTT supports the theory of spatiomotor conversion proposed by Hikosaka et al.[12] Motor skill improvement does not only proceed motor-based, but also requires a perceptual component. In the SRTT, movement-based learning is performed by continuously repeating the out-played sequence with a certain order of finger movements. The perceptual, or goal-based learning component consists of acquiring the repeating sequence of visual cues on the screen and associating it with the corresponding answer keys.[13]

The test participants first train the repeating sequence of the SRTT - including two blocks of randomly ordered trials next to the repeating sequence - with their dominant hand. Once the repeating sequence is subconsciously acquired, the two skill components are distinctly tested by probing the skill with the other hand. By switching hands, the same response button is not connected with the same finger anymore (Fig. 3). Thus, by presenting the same pattern of visual cues the finger movements have to change to achieve the same goal. Alternatively, it is

[12] View 1.2 The Central Mechanisms of Motor Skill Learning

[13] The perceptual goal-based acquisition of the repeating sequence is also called effector-independent, or spatial learning.

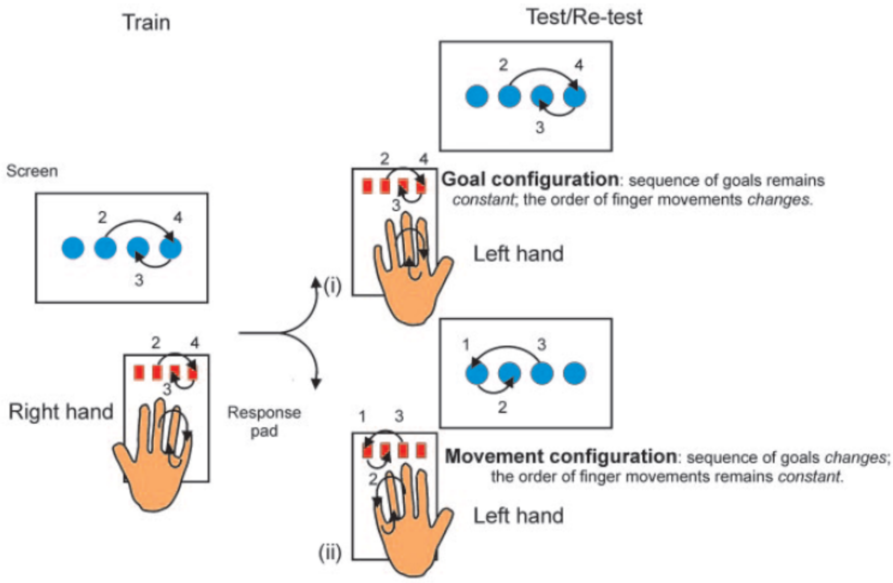

Figure 3: "Design used to dissociate goal- and movement-based skill improvements. Visual cues presented on a screen guide the acquisition of skill during practice. Skill in this task is due to learning a series of finger movements (e.g., -middle-little-ring) combined with learning a sequence of response buttons (e.g., -2-4-3), or goals. Switching hands makes it possible to distinguish between these skill components: (i) maintaining the goal (e.g., -2-4-3) but altering the order of finger movements (goal configuration) measures the skill derived from knowledge of the goal (i.e. knowledge of the sequence, independent of the fingers used), whereas (ii) maintaining the order of finger movements (e.g., -middle-little-ring) but altering the goal (movement configuration) measures the skill derived from the finger movements (i.e. knowledge of the specific finger movements, independent of the sequence of response buttons). This later type of manipulation produces a mirror sequence [e.g., from -2-4-3 to -3-1-2,]." (D. A. Cohen et al., 2005) [2]

also possible to keep the sequence of finger movements the same[14] and adapt the pattern of the repeating visual cues accordingly. In this manner the movement is preserved and the goal altered. In this way, two SRTT configurations are generated: the goal configuration that is testing goal-based learning and the movement-based configuration, also called action-configuration, that is testing movement-based sequence-learning.

This provides the possibility to test spatial and motor domains of the brains motor pathways (Fig. 1) engaged by the SRTT individually.

2.2 Methodological Issues

It is our goal to adapt the SRTT of Cohen et al. [2] so that we can measure the spatial skill learning improvement focalized individually on each participant. We adopt Cohen's method as

[14]E.g. the right hand sequence 2-4-3 (index - ring - middle finger right hand) is mirrored and becomes 4-2-3 (index - ring - middle finger left hand) to obtain the movement-based left-hand configuration.

a basis with four major and several minor amendments.[15] To do this, we created a set of rules that needs to be taken into consideration when generating the modified SRTT:

(i) Traditionally, participants solve the SRTT one time with their dominant hand and perform subsequently the goal- or the movement-based SRTT with the other hand. However, this method provides no possibility to ascertain that the initial motor sequence has been learned in first place with the dominant hand. Each participant has an individual learning pace and especially neurologically impaired participants could need more time for the acquisition of the repeating sequence that is bedrock to the SRTT. Hence, participants require an individual confirmation of their acquisition of the sequence.

(ii) Next to the subconscious acquisition of the repeating sequence, the participant also gradually improves visuomotor associations between the visual cue and the response key. This process called *Mapping* does also occur without the repeating sequence and describes task-solving skill improvement - the mere clicking of the corresponding button to the appearing visual cue. This factor must not be neglected because when visuomotor associations are learned in isolation, for instance as participants perform exclusively random trials, substantial reductions in reaction time indicating a learning process are still detected [12]. These reductions in reaction time can distort the results of goal- and movement-based reaction time tests.

(iii) To maximize the reaction time difference between the random and the sequential trials, random trials that are fully independent from each other need to be guaranteed. Thus, to minimize the predictability of the visual cues, double repetitions of the same spatial position (e.g. -1-1) should be avoided. Such repetitions render the random trials involuntarily easier for the participant, thus they allow a faster response. Furthermore, there must be no repeating sequence of any length within the blocks of random trials, since the participant might otherwise acquire this sequence aside or instead of the real repeating sequence.

(iv) To minimize the participant's awareness of the repeating sequence, this sequence should

[15] The minor amendments consist of SRTT code derivations from Cohen's SRTT in terms of simplifications.

be at most imperceptible.[16] For instance, in the original 10-item N & B sequence 4-2-3-1-3-2-4-3-2-1 position 2 and 3 occur three times whilst position 1 and 4 are only displayed two times. Thus, the probability of the next cue appearing at a certain position is not equally distributed over all four positions, allowing the participant to make predictions about the sequence. Furthermore, sandwich repetitions (e.g. -3-1-3-) are very likely to be detected when the sequence is repeated multiple times.

2.3 Methodological changes

The methodological issues were addressed by generating a raw modified version of the SRTT by using the Cogent computer package for MATLAB. Ensuing to this, we ran a pilot study for calibration purposes on healthy participants.

(i) We define achieved acquisition of the repeating sequence by attainment of a threshold of reaction time difference between the trials of the repeating sequence and trials of the blocks of randoms[17]. This threshold is calculated with data won from a pilot study, run on healthy participants. By contrasting the average reaction times of the random to the sequential reaction times, an approximated percentage of decrease in reaction time taking place over the course of the SRTT is detected. Premeditatedly that a group of neurologically healthy participants ought to acquire the repeating sequence faster than all other groups, they perform the SRTT two times with their right hand. During the second right-hand performance, the decrease in reaction time is measured. The on average measured reduction in reaction time across the course of the SRTT is considered as threshold that neurologically impaired participants need to achieve to perform the goal- or movement-based SRTT.

(ii) To give proof for actual motor skill improvement instead of mere mapping appearances, we generated a control configuration next to the goal-based and action-based configuration. The repeating sequence of this configuration is fully different from the original repeating sequence (i.e. the order in which trials follow each other is altered). The different sequence is generated by the same standards as the original sequence, thus does not have any noticeable features that would bring the sequence into the participant's awareness. Significant reduction in reaction time when testing the participant with the control configuration

[16] Awareness of the repeating sequence should be possibly minimized to prevent explicit learning and ensure implicit skill improvement.

[17] A block of randoms describes a block of visual cues that are displayed in a random order.

would imply development of mapping skills instead of sequence learning.

(iii) To amend the random trials problem we suggest a range of eighteen different sets of specific 50-item random trials. These generated trials hold no noticeable features such as double repetitions of the same cue or a repeating sequence.

(iv) The original 10-item N & B sequence was extended with 2 more items, generating a 12-item sequence allowing each position to occur three times and be followed each time by a different position (e.g. position 4 is ensued once by position 1, once by position 2 and once by position 3). Thus the probability of the next cue appearing on one of the three other remaining positions is equally distributed. Adversely, it is due to the nature of a 12-item sequence and under the condition of equal distribution not possible to avoid at the minimum one sandwich-sequence within the repeating sequence.

2.4 MATLAB Cogent

The enumerated changes were addressed by generating a SRTT by using a Cogent computer package containing both Cogent Graphics and Cogent 2000.[18] Cogent Graphics is a graphics toolbox for MATLAB, used to generate real time graphical animations for use as stimuli in vision research and to monitor subject input via keyboard and mouse. Cogent 2000 is a complete MATLAB-based software environment for functional brain mapping experiments, containing commands useful for presenting all kind of stimuli [15]. After having generated a raw modified version of the SRTT, we ran a pilot study on healthy participants for calibration purposes.

2.5 SRTT Configuration

2.5.1 Configuration Concept

In our model of the SRTT, participants first test their dominant hand. This dominant hand configuration consists of a repeating sequence sandwiched by two blocks of random trials (Fig. 4). The two random blocks are each 50 visual cues long. The repeating sequence is 12 items long and is repeated 15 times. The next visual cue is presented almost instantly after the correct response button is pressed.[19] In the goal-based configuration the repeating sequence is played

[18]The MATLAB code for the right-hand configuration, from which the left-hand configurations were derived, is to be found in the Appendix: A.4 MATLAB Code.

[19]The next visual cue is presented after a fixed delay of 400ms.

out in the same order as in the dominant-hand sequence. The action-based sequence is the mirrored version of the dominant-hand sequence.[20]

R_1 (50)	S (11·12)	S (4·12)	R_2 (50)

Figure 4: Concept of trials orders in the SRTT: a 15-repeats 12-item sequence sandwiched by two blocks of 50 visual cues appearing in a random order.

The control configuration consists of the same structure as the dominant-hand configuration, yet with a new 12-item fully independent sequence. The random blocks (R_1, R_2) are different and specific to each of the SRTT configurations.

2.5.2 Calculation

It is our aim to guarantee that participants of any neurological state acquire the repeating sequence subconsciously before they switch hand to perform the goal- or action-based configuration. To do this, the participants are required to improve their reaction time over course of the SRTT by a certain percentage. This percentage of improvement is based on the comparison of the participants reaction time for the first random block to the reaction time difference between the repeating sequence and the second random block, subsequent to the repeating sequence.

$$\frac{RT_{R2} - RT_{S48}}{RT_{R2}} = \frac{x}{100} RT_{R1}$$
$$b = \frac{x}{100} a$$

Participants of the pilot study perform the SRTT two times with their dominant hand and one time with their non-dominant hand. For the threshold calculation only the second dominant-hand performance is taken into consideration. From the 15 repeats of the 12-item sequence, only the last 4 repeats (48 trials) are considered. This inflates on the one hand the reaction time difference between sequential and random trials and gives the participant on the other hand enough chance to improve repeating sequence performance skills. To measure motor skill improvement across the course of the performance, the average difference of reaction time for trials of the second block of random trials (RT_{R2}) and of the repeating sequence (RT_S) account for b. b is the equivalent to a certain percentage of a - the average reaction time needed for trials in the first block of randoms (RT_{R1}). a and b are values individual to each participant.

[20]View 2.6.2 Setup

Finally, x is the reaction time improvement that is obtained by contrasting b to a, thus by illustrating the reaction time improvement over the course of the SRTT. The x investigated in the pilot study is the reaction time improvement participants subsequent to the pilot study need to acquire to confirm acquisition of the repeating sequence. The advantage of a percental value is that it is a comparison to personal performance and achievement. Such a threshold is a more flexible solution to guarantee acquired skill than a fixed speed limit[21].

2.6 Calibration Pilot Study

2.6.1 Participants

The pilot study was designed to test the average difference in reaction time of healthy participants for visually presented stimuli by making an instant connection to a motor sequence. Twenty right-hand-dominant participants were recruited. At the end of the study, six participants were removed from further analysis, because they were able to recall in a free recall test[22], more than four items of the test sequence. This greater-than-chance recall[23] can prevent an unbiased starting condition after the dominant-hand configuration towards the non-dominant-hand configurations. Data was analyzed from the remaining 16 participants (8 male, 8 female; 20.9 $\pm$ 0.6y) who were randomly distributed across the three groups: goal-based, action-based and control configuration.

2.6.2 Setup

Our modified version of the SRTT was utilized to monitor the acquisition of a finger movement sequence.[24] A solid white circular stimulus (diameter, 20mm; viewed from 800mm) appeared on a black monitor at one of four possible positions within an equally spaced horizontal array (Fig. 5). The presentation of each stimulus was controlled by a computer using software we designed specifically to record reaction times (MATLAB; Cogent). Each of the four possible positions corresponded to one of the four buttons on the computer keyboard, on which the participants fingers rested. When a target appeared, participants were instructed to respond by pressing the appropriate button on the pad as quickly as possible. Having made the correct response,

[21] A fixed speed limit describes a threshold for when a reaction time of x ms is achieved.

[22] In a free recall test, a participant is presented a number of items to memorize one after the other. At the end of the presentation the participant is asked to repeat the items without aid of the examiner, which gives the test its name [16].

[23] Greater-than-chance-recall indicates that if more than one third of the repeating sequence can be recalled, then the sequence was learned explicitly.

[24] This entire setup is partly literally based on a SRTT experimental setup by Cohen et al. [2], as we conducted only few setup adaptions for our SRTT setup requirements.

the cue on the screen disappeared and was replaced by the next cue after a delay of 400 ms. If the participant made an incorrect response, the stimulus remained until the correct button was selected. The task was described to participants as a test of reaction time; however, the position of each cue followed, unbeknownst to the participant, a regular and repeating 12-item pattern (2-3-1-4-3-2-4-1-3-4-2-1). There were three SRTT configurations. Each participants had to perform the initial sequence (2-3-1-4-3-2-4-1-3-4-2-1) two times with the right hand before switching to the left hand. On the left hand all three configurations were tested: the goal-based sequence (2-3-1-4-3-2-4-1-3-4-2-1), which equaled the initial configuration, the action-based sequence (3-2-4-1-2-3-1-4-2-1-3-4), which was the mirrored goal configuration, and the control sequence (4-1-3-2-1-4-2-3-1-2-4-3), which was newly generated and as independent as possible from the initial configuration. Among these fourteen participants five were tested on the goal-based configuration, seven on the action-based configuration and two on the control sequence configuration.[25]

Figure 5: Example for a four-item sequence of visual cues presented in the SRTT by Cogent in MATLAB. Generic sequence is 1-3-4-2.

3 Results

3.1 Data Analysis

The results were analyzed with a two-way repeated measures ANOVA through SPSS [17], a software used for statistical analysis.

A repeated measures ANOVA compares three or more group means where participants stay the same in each group. This usually occurs in two situations: when participants are measured multiple times to see changes in an intervention; or when participants are subject to more than one condition or trial and response on each of these conditions or trials wants to be compared [17]. By making comparisons within and between groups, the repeated measures ANOVA allows analysis of the interaction, i.e. how multiple factors may influence a certain behavior. These

[25] Originally, the goal- and the action-based group held both seven participants, while the control group held six participants.

factors can be analyzed independently, which is why they are called *independent variables.* To each independent variable a certain number of *related groups* is subordinate.

In the context of the pilot study, the independent variables to investigate the difference in RT are *hand* and *condition.* Each of these two independent variables has several related groups, that are the independent variable points. These related groups are tested in the experiment. The independent variable *hand* has two related groups called *right* and *left. Right* is the RT from the second right-hand and *left* is the RT from the left-hand SRTT performance. For *condition*, there are three related groups: *action*, *goal* and *different sequence.* There are two related groups in *hand* and three in *condition*, which is why we are doing a 2 x 3 repeated measures ANOVA.[26]

A repeated measures ANOVA run through SPSS requires at least three of a list of five assumptions that are acquired by our calibration study:[27]

(i) *The dependent variable is measured in a continuous level.* In the pilot study, RT improvement is measured as percental difference in RT over the course of the SRTT in terms of comparing b to a.[28]

(ii) *The independent variable consists of at least two categorical related groups.* The independent value *hand* has two (right, left) and the independent value *condition* has three related groups (action, goal, different sequence).

(iii) *There are no significant outliers in the related groups.* Six significant outliers in the related groups of the pilot study results were excluded of the statistics. Significant outliers can have a negative effect on the repeated measures ANOVA: by altering the difference between the related groups, they can reduce the accuracy of the results.

3.2 Hand effect

Measure of interaction within the independent variable *hand* was a within-subjects measure since each participant did both conditions, i.e. each person did the sequence with both their right and left hands. Condition points are the average differences in RT of the first and second right-hand and the one left-hand SRTT performance of all participants. The effect of hand was statistically insignificant on the difference in RT (Fig. 6): $F(1,14) = 1.10$, $p = 0.311$, $\eta = 0.73$.

[26] View Appendix: A.3.1 A more detailed explanation of the rANOVA
[27] View Appendix: A.3.2 Required Assumptions for rANOVA in SPSS
[28] Compare 2.5.2 Calculation

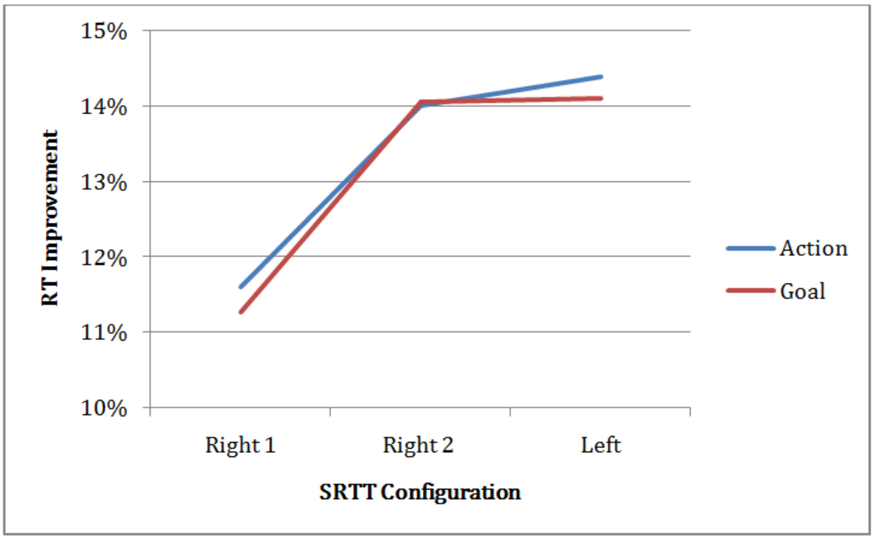

Figure 6: The current graphic, accounting for the development of the hand effect, and the two following graphics (Fig. 7, Fig. 8) illustrate the average RT improvement of the participants across the course of the three SRTT configurations. Each configuration consists of a first block of random trials, a block repeating the same 12-item sequence and a second block of random trials. Improvement is measured by comparing the required reaction time for the second and the first block of random trials. Speaking about the reaction time required for the second block of random trials, the average difference in reaction time from the second block of randoms and the repeating sequence is addressed.

3.3 Condition effect

The averaging across the four conditions accounting for *hand* and the three related groups of *condition* did not differ in the RT measure, as the effect of the independent variable *condition* was statistically insignificant: $F(2{,}14) = 1.02$, $p = 0.385$, $\eta = 0.127$.

3.4 Interaction Hand and Condition

We expected the interaction in participants performance to remain constant across the two right hand configurations, since that was prior to when we matched the second sequence with action, goal, or the different sequence. Investigated was the development of each condition from the right to the left-hand configurations and if at the left hand-configurations, they differed from one another. As the interaction of the independent variables had no statistically significant effect on the difference in RT, this was not the case (Fig. 7, Fig. 8): $F(2{,}14) = 0.67$, $p = 0.526$, $\eta = 0.088$.

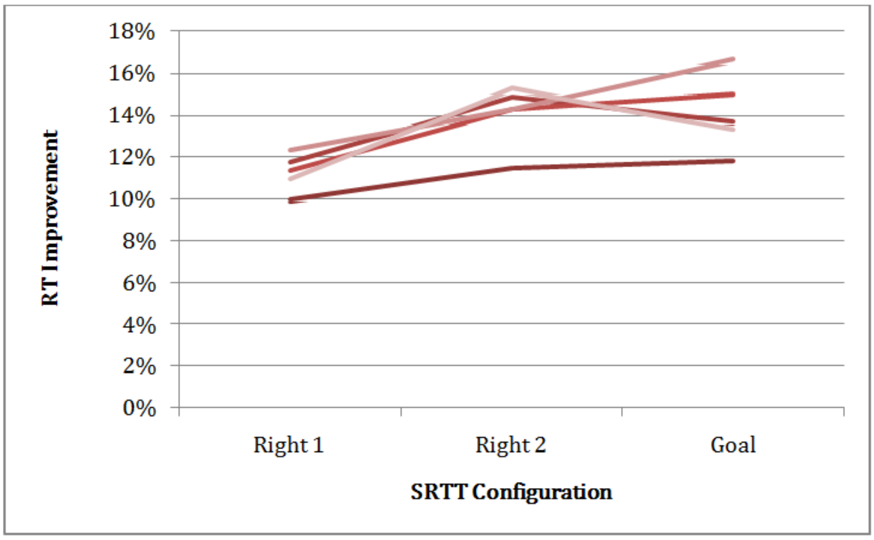

Figure 7: The RT development of the related group *Goal*, illustrated with the average RT of five test subjects.

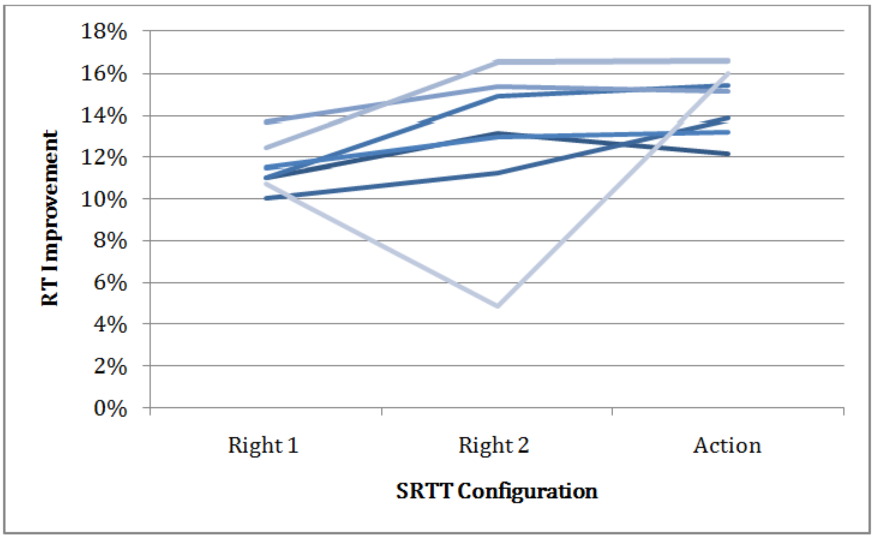

Figure 8: The RT development of the related group *Action*, illustrated with the average RT of seven test subjects.

3.5 Threshold

The reaction time threshold was calculated with the obtained data. To perform the left hand configuration, participants subsequent to the pilot study are required to achieve this threshold with their reaction time improvement across the second dominant-hand performance.

For the calculation, the average reaction achieved for the first and the second block of random trials in the right hand configuration (RT_{R1}, RT_{R2}), as well as the average of reaction time for the repeating sequence (RT_S) were inserted in the discussed equation[29].

$$x = \frac{a}{b} \times \frac{1}{100}$$

Considering the obtained data[30], the calculated threshold value is $x = 14.25\%$ reaction time improvement from the beginning to the end of the second dominant-hand SRTT performance.

4 Discussion

Skill transfer in terms of shorter reaction time from the right to the left hand configuration would suggest subconscious acquisition and recognition of the repeating sequence. However, the obtained statistically insignificant results for the hand effect suggest that there was no skill improvement across the right and the left hand. According to these results, the participants neither deteriorated, nor improved their skill. In regard of the insignificant condition effect, there was no difference in reaction time across the three related condition groups *goal*, *action* and *different sequence*. As significant difference in between the related condition groups would indicate a neurological bias to one of them, this result might show that healthy participants' performance capabilities are not prejudiced to any of the conditions. Finally, interaction between the right and the left hand configuration oughts to indicate a relation between the learned sequence and the left-hand performance. However, results for the interaction are insignificant, suggesting that participants performed the left-hand configuration in disregard of the right-hand configuration. In respect of the given results, the threshold calculated for neurologically impaired participants is rendered insignificant.

With regard to the insignificant results of the pilot study and the theoretical character of the SRTT, it is most probable that participants were exposed to various error sources.[31] These error sources can be divided into environmental and theoretical errors.

Concerning the environmental errors, the testing conditions were characterized by noise and other confounders so that participants were most likely not able to focus solely on the present SRTT. In future experiments, participants should be tested in a quiet and dimmed room that leaves enough space to focus on the present task. With regard to the theoretical errors, there are three main error sources that might account for the results. Firstly, a group of only fourteen

[29]View 2.5.2 Calculation

[30]View Appendix: A.2 Data

[31]The character of the SRTT deduces that motor learning tests like the SRTT do not follow rigid but rather science-orientated rules.

participants is a too small group to account for statistically significant data, or give evidence for an interaction. Therefore, future studies should extend the population group so that the results are rendered relevant. Secondly, it is very well possible that due to the nature of the SRTT, only mapping but no sequence skill was acquired. This leads to the assumption that either the repeating sequence was too difficult to recognize and / or to remember, or a double repetition of the sequence with the right hand was a too short presentation to subconsciously memorize the sequence. Hence, in future studies should be laid focus on the investigation of sequence alterations (such as shortening or simplification of the sequence) and alteration of the number of right hand sequence repetitions. Despite the number of sequence repetitions, yet the calculation for the reaction time threshold would stay the same as it does not depend on any repetition factors. Thirdly, several participants remarked retroperspectively to the SRTT that they were piano players or professional video-game players. As their reaction times were visibly shorter than those of the remaining participants, future studies should detect this preferred group of participants prior to the SRTT and adapt the difficulty of the repeating sequence in the task accordingly to their skill.

Finally, this sort of motor learning tests does not follow rigid rules but rather empirical theories. Hence it is always difficult to be definitely sure that theory, setup, conduct and interpretation of the experiment are valid.

In total, the modified SRTT has responded to various requirements for advanced motor learning tests, yet needs thorough refinement before it is qualified to test neurologically impaired participants with significant results.

5 Conclusion and Future work

This study was designed to create a tool to investigate implicit motor learning individually for all participants, a method which was facilitated by the SRTT. We aimed on individualizing the test by generating a threshold based on each test subject's individual motor-sequence learning improvement. The findings of the conducted pilot study suggest that the skill-transfer of a subconsciously acquired repeating sequence did not take place over the hand-transfer from the right to the left hand. Hence no significant reaction time threshold that future participants are required to achieve before motor or spatial memory testing was defined.

The modified SRTT can be reused for a variety of future studies, but has significant room for improvement. The reaction time difference and consequently the significance level may be increased by giving the random and repeating sequence more complexity. This is achieved by increasing the length of the sequence and simultaneously raising the number of right hand configurations repeats. In addition to this, subsequent skill retention studies[32] should be conducted to ascertain implicit and not explicit learning, which sets in with the processing of the skill.

The current study should be extended in two steps. First, it should be tested whether participants perform an actual skill transfer from the right to the left hand, or if they only improve mapping skills. In the latter situation, after assigning the form of acquisition, the participant should be given a manipulated Serial Reaction Time Task. In this task, colored stimuli are presented to the participant, whom is told that every time a certain color appears, a repeating sequence is displayed. Unbeknownst to the participant, another color is also following a repeating sequence. Thus, the participant is aware of learning a new sequence whilst he is subconsciously thought to learn another one, too [12]. By bringing the acquisition of the explicit and the implicit sequence in contrast, actual skill transfer might be observed.

Secondly, the group of participants should be enlarged with high school students. In case that findings of adolescents studies showed that teenagers performed the SRTT significantly better than other tested age-dependent groups, their threshold values could be applied as general SRTT threshold. The fittest reference group may account optimally for an achievable reaction time, even for participants with deteriorated brain regions.

In other words, SRTT results of a range of age-dependent groups should be compared. This could also give evidence for the development of implicit motor skill learning in the aging process. Other factors, such as activity difference between motor cortex and prefrontal cortex should be tested in future studies, for instance by contrasting them in a consecutive action-goal-based configuration.[33]

Finally, future work should systematically test the coherence between deteriorated brain regions and corresponding SRTT results. Based on the findings, the extent of neural deterioration could be measured in a continuous level, providing investigator and participant with an exact knowledge of the participant's brain condition. By deriving such information from SRTT results, we hope one day to be able to facilitate therapy possibilities for diseases such as Alzheimer's disease, as they primarily deteriorate frontoparietal areas in their early stages [18]. Enlargement of knowledge of the specific neurally deteriorated brain location might give

[32] Retention studies are investigating offline learning during a sleeping phase.

[33] Two generic examples of a consecutive left-hand configuration: 1. block of randoms - goal-based sequence - block of randoms - action-based sequence - block of randoms; 2. block of randoms - goal-based sequence - action-based sequence - block of randoms.

rise to new non-invasive therapy methods such as repetitive Transcranial Magnetic Stimulation (rTMS). In this method, neural currents are interfered with electric currents by a coil via electromagnetic induction. Traditionally, this method is used to measure the extent of deterioration of an association between a brain region and the corresponding muscle after a stroke. However, there is evidence for the stimulating role that rTMS can play in sequential learning therapy [19]. Possibilities for future work are not limited to the aforementioned; studies of motor behavior were and will always be exciting avenues for research.

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A Appendix

A.1 Abbreviations

SRTT	Serial Reaction Time Task
BG	Basal Ganglia
CB	Cerebellum
RT	Reaction Time
rTMS	repetitive Transcranial Magnetic Stimulation

A.2 Data

Configuration	Mean	Standard deviation	Variance
Right 1	0.1139	0.0105	0.000111
Right 2	0.1327	0.0309	0.000957
Goal	0.1462	0.0162	0.000262
Action	0.1411	0.0184	0.000339

Hand effect	$F(2,14) = 1.10$, $p = 0.311$, $\eta = 0.73$.
Condition effect	$F(2,14) = 1.02$, $p = 0.385$, $\eta = 0.127$.
Interaction Hand and Condition	$F(2,14) = 1.02$, $p = 0.385$, $\eta = 0.088$.

A.3 Repeated measures ANOVA

A.3.1 A more detailed explanation of the rANOVA

A repeated-measures ANOVA is a powerful statistical test because it allows to make comparisons within groups, between groups, and to analyze what is called an *interaction*. An interaction is how multiple factors may influence a certain behavior. For example, one might hypothesize that people buy more ice cream during the summer because it is: 1. hot and 2. people are outside more. These factors, that are called *independent variables* can be analyzed independently. The independent variable of the first factor, *hotness*, could be a positive one - the hotter it is, the more ice cream people buy. Likewise, the independent variable of the second factor, *people being outside more*, might also be positive - the more time that people spend outside, the more they buy ice cream. However, the interaction in this case may have the best explanation for what's happening- when it's hot outside and when people are outside more, they buy the most ice cream.

In the context of the pilot experiment, the independent variables are: 1. *hand* and 2. *condition*. For the statistics, hand has two related groups - the RT from Right 2 and the RT from the sequence they did with their left hands. For condition, there are three types of values: 1. action, 2. goal, and 3. different sequence. Because there are 2 factors in *time* and 3 in *condition*, we are said to be doing a 2 (hand: Right, Left) x 3 (condition: action, goal, different sequence) repeated-measures ANOVA.

In order to understand this test, it should first be understood what *significant* means in statistics. Using what is called a *95% confidence interval*, the results between conditions should differ from one another enough that there is only a 5% chance (or lower) that this result was by chance and not from an actual effect. This is reflected in the *p-value*. The p-value itself is a reflection of the F-value - the higher the F value, the greater the difference between conditions. The third statistically analyzed factor is partial-eta squared. This is a reflection of *power*. Power is important because it allows the distinction between effect sizes. Going back to the analogy from earlier, a small effect size might mean that people only get more ice cream one time more during the summer than the winter, whereas a large effect size might rather mean people getting ice cream ten times more during the summer than in the winter. Power is important because it is saying something that significance does not: if it is observed that, on average, people got ice cream one time more in the summer than in winter, it is a small effect size, but could be significant if the effect is consistent across, say, 1000 people. So while this is significant, it is not a big effect. The convention for the partial eta-squared is that 0.1 = small effect size, 0.3 = medium effect size, and 0.5 = large effect size.

A.3.2 Required Assumptions for rANOVA in SPSS

Full List:

Assumption 1: The dependent variable should be measured at the continuous level (i.e., they are interval or ratio variables).

Assumption 2: The independent variable should consist of at least two categorical, "related groups" or "matched pairs". "Related groups" indicates that the same subjects are present in both groups. The reason that it is possible to have the same subjects in each group is because each subject has been measured on two occasions on the same dependent variable.

Assumption 3: There should be no significant outliers in the related groups. Outliers are simply single data points within your data that do not follow the usual pattern.

Assumption 4: The distribution of the dependent variable in the two or more related groups should be approximately normally distributed.

Assumption 5: Known as sphericity, the variances of the differences between all combinations of related groups must be equal.

A.4 MATLAB Code

This is the code used for the right-hand configuration. The left-hand configurations were derived from this code and do only differ in the random trials and the repeating sequence.

A.4.1 Setup

Setup of the right-hand configuration, defining presented screen. Clear all and save file under Subject ID.

```
function SRTTright
clear all;
results.ID = input('Subject ID?', 's');

% Configures display and keyboard
config_display(1, 5, [0 0 0], 'Helvetica', 30, 10);
config_keyboard;

% Start Cogent 2000 (Note: you cannot use cogent 2000 commands in a cogent
% graphics window, but can use cogent graphics commands in cogent 2000)
start_cogent;

% Show the possible positions on the screen until any button is pressed
cgpencol(1,1,1);
cgellipse(-570,0,100,100,'f');
cgellipse(-190,0,100,100,'f');
cgellipse(190,0,100,100,'f');
cgellipse(570,0,100,100,'f');
cgflip(0,0,0) % Flips ellipses to the front

% Wait until response before continuing
waitkeydown(inf);

% Press any key to continue
cgpencol(1,1,1);
cgfont('Helvetica',30);
cgtext('Press any key to continue',0,0);
cgflip(0,0,0);
waitkeydown(inf);

% Define order of stimuli
sequence = [2 3 1 4 3 2 4 1 3 4 2 1];

% Define randoms
random1 = [4 2 3 4 3 4 1 4 2 3 2 1 3 1 2 4 3 1 2 1 3 2 1 4 2 4 3 1....
    3 2 1 3 2 1 4 2 3 4 1 2 4 3 1 2 4 2 4 3 4 1];
random2 = [4 2 3 4 1 2 4 3 1 2 1 3 2 3 4 3 1 2 4 3 1 3 2 1 3 2 1 4....
    1 2 4 3 4 3 4 1 2 1 3 2 1 4 2 3 4 1 4 2 3 2];
```

A.4.2 First 50 random trials

Set trial number as 0 for counter. Contain RT calculation for first 50 random trials.

```
trnumrand1 = 0;          % Set trial number as 0 for counter
t0 = time;               % Set time 0 at the start of every random presentation
cgpencol(1,1,1);         % Set circle color as white

% Present first 50 random trials
for Random = random1
    if Random == 1;
        cgellipse(-570,0,100,100,'f');
        t1 = cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 36);     % Press "9" for position 1
    elseif Random == 2;
        cgellipse(-190,0,100,100,'f');
        t1 = cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 27);     % Press "0" for position 2
    elseif Random == 3;
        cgellipse(190,0,100,100,'f');
        t1= cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 53);     % Press "-" for position 3
    elseif Random == 4;
        cgellipse(570,0,100,100,'f');
        t1 = cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 54);     % Press "=" for position 4
    end

    trnumrand1 = trnumrand1+1;      % Increase trial number by 1 each trial for the counter
    readkeys;                       % Read keys
    wait(400);                      % Wait 400ms between trials

    % Log RT
    results.AnsKey1(trnumrand1, Random) = kp;                   % original keynumber (saved for safe)
    results.Keytime1(trnumrand1, Random) = t1 - t0;             % time at which key was pressed
    results.RTrand1(trnumrand1, Random) = kt-t1;                    % log reaction times
    RT = results.RTrand1(trnumrand1, Random);                       % define RT

end

% Analysis of rand1 trials
for Random = random1
    RTrand1 = 0;                % Calculate RTs; RT132 = RT for first 50 random trials
    RTrand1 = RTrand1 + RT;     % Log results and calculate Avg of first 50 random trials
    results.RTrand1avg = RTrand1/50;
end
```

A.4.3 Stimulus 132

There are 11 blocks of the repeating sequence.

```
BlkNum = 11;                    % There are 11 blocks of the sequence
trnum132 = 0;                   % Set trial number as 0 for counter

for Block = 1:BlkNum            % Repeat stimulus sequence 132 times (11 loops) without RT
    clearkeys;                  % Clear keys
    t0 = time;                  % Set time 0 at the start of every stimulus presentation
    cgpencol(1,1,1);            % Set circle color as white
    for Trial = sequence        % Tell cogent where to draw each circle
        if Trial == 1;
            cgellipse(-570,0,100,100,'f');
            t1 = cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 36);     % Press "9" for position 1
        elseif Trial == 2;
            cgellipse(-190,0,100,100,'f');
            t1 = cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 27);     % Press "0" for position 2
        elseif Trial == 3;
            cgellipse(190,0,100,100,'f');
            t1= cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 53);     % Press "-" for position 3
        elseif Trial == 4;
            cgellipse(570,0,100,100,'f');
            t1 = cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 54);     % Press "=" for position 4
        end

        trnum132 = trnum132+1;          % Increase trial number by 1 each trial for the counter
        readkeys;                       % Read keys

        wait(400);                      % Delay 400ms inbetween trials

        % Log RT
        results.AnsKey(trnum132, Block) = kp;               % original keynumber (saved for safe)
        results.Keytime(trnum132, Block) = t1 - t0;         % time at which key was pressed
        results.RTseq132(trnum132, Block) = kt-t1;          % log reaction times
        RT = results.RTseq132(trnum132, Block);             % define RT

    end

end

for Block = 1:BlkNum                    % Analysis of sequence 132 trials
    for Trial = sequence
        RT132 = 0;                      % Calculate RTs; RT132 = RT for 132 trials
        RT132 = RT132 + RT;
        results.RT132avg = RT132/132;   % Log results and calculate Avg of 132 trials
    end
end
```

A.4.4 Stimulus 48

Only these 4 blocks are compared with the following 50 random trials.

```
BlkNum48 = 4;                   % There are 4 blocks of the sequence
trnum48 = 0;                    % Set trial number as 0 for counter

for Block = 1:BlkNum48          % Repeat stimulus sequence 48 times (4 loops) without RT
    clearkeys;                  % Clear keys
    t0 = time;                  % Set time 0 at the start of every stimulus presentation
    cgpencol(1,1,1);            % Set circle color as white
    for Trial = sequence        % Tell cogent where to draw each circle
        if Trial == 1;
            cgellipse(-570,0,100,100,'f');
            t1 = cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 36);     % Press "9" for position 1
        elseif Trial == 2;
```

```
            cgellipse(-190,0,100,100,'f');
            t1 = cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 27);     % Press "0" for position 2
        elseif Trial == 3;
            cgellipse(190,0,100,100,'f');
            t1= cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 53);     % Press "-" for position 3
        elseif Trial == 4;
            cgellipse(570,0,100,100,'f');
            t1 = cgflip(0,0,0);
            [kp,kt] = waitkeydown(inf, 54);     % Press "=" for position 4
        end

        trnum48 = trnum48+1;        % Increase trial number by 1 each trial for the counter
        readkeys;                   % Read keys
        wait(400);                  % Delay 400ms inbetween trials

        % Log RT
        results.AnsKey(trnum48, Block) = kp;                % original keynumber (saved for safe)
        results.Keytime(trnum48, Block) = t1 - t0;          % time at which key was pressed
        results.RTseq48(trnum48, Block) = kt-t1;            % log reaction times
        RT = results.RTseq48(trnum48, Block);               % define RT

    end

end

for Block = 1:BlkNum48              % Analysis of sequence 132 trials
    for Trial = sequence
        RT48 = 0;                   % Calculate RTs; RT132 = RT for 132 trials
        RT48 = RT48 + RT;
        results.RT48avg = RT48/48;  % Log results and calculate Avg of 132 trials
    end
end
```

A.4.5 Last 50 random trials

Set trial number as 0 for counter.

```
trnumrand2 = 0;                    % Set trial number as 0 for counter
t0 = time;                         % Set time 0 at the start of every random presentation
cgpencol(1,1,1);                   % Set circle color as white

for Random = random2               % Present last 50 random trials
    if Random == 1;
        cgellipse(-570,0,100,100,'f');
        t1 = cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 36);     % Press "9" for position 1
    elseif Random == 2;
        cgellipse(-190,0,100,100,'f');
        t1 = cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 27);     % Press "0" for position 2
    elseif Random == 3;
        cgellipse(190,0,100,100,'f');
        t1= cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 53);     % Press "-" for position 3
    elseif Random == 4;
        cgellipse(570,0,100,100,'f');
        t1 = cgflip(0,0,0);
        [kp,kt] = waitkeydown(inf, 54);     % Press "=" for position 4
    end

    trnumrand2 = trnumrand2+1;              % Increase trial number by 1 each trial for the counter
    readkeys;                               % Read keys
    wait(400);                              % Wait 400ms between trials

    % Log RT
```

```
    results.AnsKey(trnumrand2, Random) = kp;                % original keynumber (saved for safe)
    results.Keytime(trnumrand2, Random) = t1 - t0;          % time at which key was pressed
    results.RTrand2(trnumrand2, Random) = kt-t1;            % log reaction times
    RT = results.RTrand2(trnumrand2, Random);               % define RT

end

for Random = random2                        % Analysis of rand2 trials
    RTrand2 = 0;                            % Calculate RTs; RTrand2 = RT for last 50 random trials
    RTrand2 = RTrand2 + RT;
    results.RTrand2avg = RTrand2/50;        % Log results and calculate Avg of last 50 random trials
end
```

A.4.6 Compiled analysis

RTskill = comparison between last 48 of sequence and last 50 random trials.

```
results.RTskill = (results.RTrand2avg - results.RT48avg)/results.RTrand2avg;

% RTimprovement = comparison of randoms at beginning vs. end
results.RTimprovement = (results.RTrand1avg - results.RTrand2avg)/results.RTrand1avg;
% RTseq180 = average of all sequence trials
results.RTseq180 = (RTrand1 + RTrand2)/180;
```

A.4.7 Save results

```
filename = sprintf('SRTTright %s', results.ID);
save (filename, 'results');

% Stop cogent
stop_cogent;
```