Applying Passive Haptic Learning to induce associative motor memory within a visual CRT experiment

by Mark van Koningsveld
m.r.van.koningsveld@umail.leidenuniv.nl
Leiden University
Supervisors: Edwin van der Heide, Stefan van der Stigchel

Abstract

We have introduced Passive Haptic learning in a standard Choice Reaction time task that consisted of a pre-test, a distraction game and a post test. We looked both at the decrease changes in reaction time and improvement of error rates. Passive Haptic Learning (PHL) is the concept of learning motor skills by receiving haptic information while performing a distractive task that asks for full attention. We created a glove-based and system that was able to provides haptic feedback corresponding to visual cues. After a pre- test where a baseline was established, both the PHL group and the control group played a game of snake. The PHL group received visual cues paired with vibrations in the corresponding fingers. We found no significant improvement in mean reaction times in the PHL group when compared to the control group, although they did perform slightly better. We did however see that the error rates of the PHL group cut in half while those of the control group stayed almost the same. Although still not significant it is meaningful to do further research into the effect of PHL on motor control programs and uses outside sequential motor learning.

1 Intro

Haptic devices using vibrational feedback have been successfully used to shorten the time it takes to learn motor skills. In most cases these devices are used while actively practising a task to enhance the learning experience (1). By providing tactile information to the participants limbs or fingers, motor skills can either be instilled in a direct and intuitive manner. Movements can also be modified by instantly correcting mistakes or providing boundaries. (2)

Passive haptic learning is a new concept that allows the user to focus on a primary task of their choice while learning takes place in the background. This effect was first utilized to help participants learn to play simple melodies on the piano. Participants wear a haptic device that places vibrational motors on each finger, providing stimuli in a repetitive pattern while they complete a distractive task. The pattern corresponds to the fingers needed to play the melody. (3)
After this passive training period, the device is taken away for the final performance. Due to induced 'muscle memory' the participants are able to perform significantly better at manual tasks. The melody or other information is translated into haptic cues and then delivered to the user as if someone 'taps'

on their fingers, guiding them through a pattern of motions. After repeating the patterns of vibration for about half an hour the information is implicitly known by the user. This type of learning makes it possible to save time by having users be able to learn during their daily routines. (4).

Up until now, passive haptic learning has mainly been used to instill sequential motor memory, like the movement patterns necessary to play a musical piece. We are interested in the question if we can use the same technique for associative memory. Associative memory deals with relations between sensorial input and choosing the right response. We make relations in our head and the stronger the relation, the quicker the response (5). We aim to pair motor responses by the fingers to visual cues presented on a screen with PHL. Using a choice reaction time test, we will measure the time it takes to select the right motor response to the presented stimulus. This will show if the connection between the choices on the screen and the right motor response was strengthened.

2 Related work

2.1 Haptic Learning

Haptic learning is the umbrella term for any type of assisted learning using different kinds of tactile feedback. The most well known versions of this are robotic guidance and vibrational feedback. Robotic guidance either lets a robot guide the participant through a series of motions much like how a teacher would guide a student, or uses the robotic element to keep the movements of subjects within the right bounds. An example of the first case is the robotic arm by Kim et al. which guided participants through a complex series of motions, making for a better learning experience than just receiving visual or auditory instructions (6).

Vibrational haptic feedback teaches motor movements using vibrational motors to relay information. Again, this can come in the form of showing either the right way to do a task or by giving feedback once a participant makes a mistake. In the experiment by Marchal-Crespo et al. tennis players received haptic cues on the right moment they had to hit a ball, while Zheng and Morrell used vibrational feedback that helps participants keep their posture within desired bounds to prevent back pain (7) (8).

Motor memory can fall under sequential memory and associative memory. Sequential motor memory includes how to tie our shoelaces, how to unlock our bike and just about any other multi-part movement. Learning sequential movements can be supported by for instance robotic guidance or vibrational patterns that vibrate muscles in the right order (9).
Our associative memories deal with relations between either multiple stimuli or a stimulus and a response. Like in the experiments by Pavlov, these connections can be reinforced with mere exposure or by reward and punishment (10). Using vibrations, visual and auditory stimuli can be linked to haptic cues. In the experiment by Newell et al. vibrations were used to enhance recollection to better recognise different scenes (11). Designing haptics for learning involves its own design guidelines. Although we can distinguish haptic cues in great detail, it is easier to learn cues that are far apart from each other (12). Besides that, there are a lot of reports on how we can start to rely too much on haptic cues, performing worse when they are taken away (14).

2.2 Passive haptic learning

Passive haptic learning is a new subject that arose from combining haptic learning for sequential motor movements and the concept of passive learning. Passive learning is all learning that occurs without the subject paying its full attention to it. The most common example is the information we pick up when a television is on in the background (15) In the original Mobile Music Touch experiment conducted at MIT, participants learned a simple melody while performing a distraction task (3). Repeated vibrations on the fingers in patterns corresponding to musical melodies were given for half an hour after which the error rate and rhythm of movements improved significantly. Since then PHL has been used to teach other instruments, typing skills and morse code. Typically these experiments involve information provided in the background and corresponding vibrations on the fingers (4) (16) (17). These vibrations are given by a haptic glove that places vibration motors on each finger.

PHL experiments involve a baseline trial followed by a passive training segment and finally a performance test. It was shown that the type of distracting task like filling out a form or doing housework did not influence the end results (4). Even when instructed to ignore these vibrations learning still occurs. Passive haptic learning seems promising in situations where there is little time to actively practise or when a novel mapping has to be introduced to participants as is the case with difficult to master braille keyboards (17). Studies are generally conducted by counting the amount of errors a participant makes before and after PHL. The improvement rates are compared and put through statistical analysis. In the Mobile Music Touch experiment, participants had to learn two melodies one of which was reinforced with PHL to make a within subject comparison (3). There is still research being conducted into the effectiveness of PHL in the long term (4).

2.3 Choice reaction time

Reaction times are used to study the time it takes for our brain to process a stimulus and for our body to respond to it. In Choice Reaction Time (CRT), there are multiple stimuli that are linked to multiple responses. Standard CRT scores are between 600 and 800 milliseconds. The time it takes to make a response steadily increases together with the amount of options the participant has to choose from (18).

CRT is frequently used to see how strong an association is in our brain. The stronger the connection is the quicker the response (19). The type of stimulus and how the subject relates to it can affect reaction time. Karate masters and students were shown pictures of certain moves that they had to respond to with a choice of counter moves. The masters took less time to asses the move and choose the right response (20). The influence of the amount of practise a participant has had doing the CRT task has also been studied. In studies conducted by Rhoades it was shown that after sufficient training the difference between two stimuli versus eight or more did not matter anymore for reaction time. Practise is typically divided into blocks of fifty to a hundred consecutive stimuli per session. (21).

Besides training there are many other effects that have been studied related to CRT. A concept often mentioned within CRT experiments is the speed-accuracy trade-off. Participants can be asked to either focus on reacting as quick as possible or make sure they do not make mistakes (22). Reaction times

consist of a cognitive reaction and a motor response time. The memory drum theory covers the cognitive part of the response. The more complex the relation that has to be made is the more time it takes synapses to make a decision.(23) Priming also affects reaction time. In an experiment by Simon J Richard, coloured buttons were used to prime participants for which key corresponded to which stimulus. (24)
Although we know that participants respond more quickly to haptic cues than to visual or auditory cues, the effects of haptic learning on reaction times have not been studied extensively (19). In research by Kim et al. however, it was found that learning patterns in a sequential reaction time task works with haptic stimulation as well as with visual cues (6).

CRT experiments are generally conducted using finger presses as reactions to stimuli that are presented on a screen or through headphones. Time between stimuli varies from half a second to two seconds with randomised intervals (19). Correspondence between the stimuli and the reaction that has to be given is of great influence on RT. If we have to press a button to the left for a stimulus which appears on our left side, it is easier than if we would have had to press a button to our right (25). Reaction times are often analysed by calculating the mean reaction time of participants. It has also been said that median reaction times are more important, because mean reaction times can be influenced by big outliers. (26)

3 Method

3.1 User study

The most important goal of this study is to see if PHL training can help shorten reaction times (HP1). The second goal is to see if PHL can lessen the amount of errors participants make (HP2). We will also analyse the data to see if any positive effects occur when we combine reaction time and error rates in analysis (HP3). There will also be a brief look at the effects of PHL on the participants performance in our distractive task.

To test the hypotheses we have created an experiment in which participants will be divided in two groups. One group will receive PHL (PHL group) and the second will not (control group). This setup is used regularly in CRT experiments (18).

Both groups will go through three phases of the experiment. In the first phase, a pre test is conducted to establish a baseline by completing a CRT test. In the second phase, called the training phase, both groups will play a game on the computer. The PHL group will experience visual cues paired with vibrational cues on their fingers corresponding to the first test. The control group will play the game without this input. In the third phase called the post test, a second reaction time

fig. 1: Schematic representation of the experiment

test will be conducted similar to the one in the first phase. A diagram of the test setup can be seen in Figure 1.

Reaction times and error rates from the post test will be compared to those of the pre test to establish a learning rate. The learning rates of both groups will be compared to see if the PHL group improved more than the control group. The scores from the game in the second phase will be compared between groups to see if the PHL group was distracted by the stimuli they received that led to lower game scores.

3.2 Apparatus

We created a haptic glove based on the designs by Lassange et al (27). We opted for a model that keeps the fingers seperate to make it easier to distinguish where vibrations are occuring. We used four vibration motors typically found in smartphones. The glove is connected to an Arduino Mega that provides current to the vibration motors. We used a standard Dell keyboard to register finger presses of participants.

fig. 2: Photo of the haptic glove

3.3 Software design

We created two separate programs, one containing the reaction time test and the other the game. The reaction time test will be used in both the pre test and the post test and is the same for both groups. The program shows participants four boxes. One of the boxes lights up prompting the participant to respond. The participant responds using the ASDF keys on the keyboard. Once the participant has responded the boxes turn dark again until the next trial. The time it took to respond is recorded and saved in a file and incorrect responses are marked. The order in which the boxes light up is randomised, although each box lights up the same amount of times to prevent using one finger more than the other. The delay between the stimuli is at least 500 milliseconds plus either 250, 500, 750 or 1000 milliseconds (8).

To make the task more challenging, the participant has to respond with the key opposite to the box that lights up. The most left box requires the participant to respond with the most right key, and vice versa. The middle two keys are equally mirrored as seen in figure 3. We have made this mapping more challenging to make the learning rate more apparent. We do this as to have more clear results about whether learning took place during the second phase.

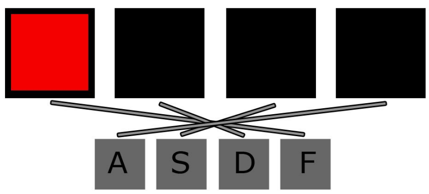


fig.3: Reverse mapping of the keys to the visual stimuli

The second program contains the game and has two different versions. The first version is presented to the control group. This version has the participant play the well known game snake using the four arrows on the keyboard. Participants control the snake which becomes longer the more food is collected on the screen. The number of deaths that occur are recorded as well as the scores that the players achieve before they die. This information is displayed in the top part of the window and is saved in a file once the game has been stopped.

The PHL group plays a version of this game but with added components to make passive haptic learning possible. During the game the same boxes that were used in the first program are placed in the middle of the screen. These boxes light up randomly in the same manner as before. At the same time, vibrational cues corresponding to the finger that is linked to this box are sent through the haptic glove. Examples of both versions of the program can be seen in figure 4. All software for this experiment is created using the processing coding language and IDE. We have used a second program to see if the reaction time program is accurate. By simulating inputs we found out that the program has a variability of 0.32 milliseconds which should be small enough not to affect the final results.

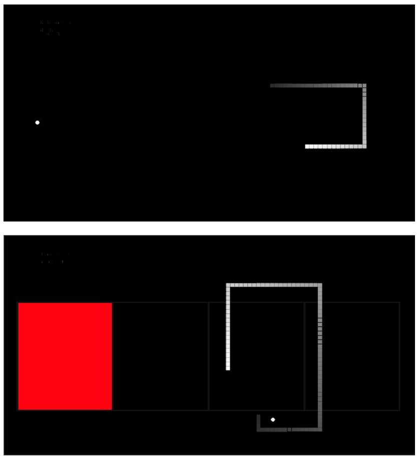


fig.4: Above the game without PHL, below the game with PHL

3.4 Participants

We have gathered 32 participants from the computer science faculty in Leiden. There are 20 male participants and 12 female. We asked participants beforehand if they were left handed or right handed. In the case of (partly) ambidextrous participants we asked which hand was used for writing. We also asked about any visual or motor deficits the participants might have. The participants were divided randomly over the PHL group and the control group, while trying to keep the average age of the two groups on the same level. The participants were not told if they were in the control group or not. They were also not told about the different phases but did get an indication of how long the full experiment would last. Participants were asked to try and optimise for fast reactions and to pay less attention to mistakes. This is the case in most CRT experiments because doing it the other way around may create outliers in the data.

3.5 Procedure

Participants were led into a secluded room in the Computer Science faculty building. Here they were asked to provide the information required for analysis. Participants were given the instructions for the first phase of the experiment and the mirrored mapping of the keys. With help from the instructor the haptic glove was put on their hand and secured. The gloved hand was placed on the keyboard and the pre test was initiated.

The pre test consists of 60 reaction trials, approximately taking one minute to complete. In other experiments there have reportedly been used between 40 and 100 trials per experiment block, sometimes divided in smaller blocks. (25) We wanted to keep the training in the first part as minimal as possible so we can clearly see the effects of PHL versus no PHL, but we also need enough trials to have a representative average base reaction time. After completing the 60 trials, the program stops and the results are saved.

At the start of the second phase, participants were asked to keep the gloved hand on the keyboard. The other hand was placed on the keyboard to play the game. The game was played for fifteen minutes. This amounts to about 1200 trials of haptic stimulation received by the PHL group while the other group gets no stimulation. Most passive haptic learning experiments use a training time of about half an hour, but due to time constraints and the more simple nature of information being learned we opted for half of this (3) (4).

After completing the game the third phase was initiated. Again there were 60 reaction time trials, amounting to a minute of testing. After all phases were completed, the PHL group was asked if the cues distracted them from playing the game, and both groups were asked if they thought they felt they did better in the second test.

3.6 Data analysis

After wrapping up the experiments the average reaction time from the pre test and the post test of each participant were calculated. The first 10 trials of both tests were discarded to make up for the time it takes for the participants to get used to the unusual mapping of the keys and prevent big outliers. This is standard practise when it comes to reaction time based experiments (28).The averages were put in a VST file and loaded into SPSS for statistical analysis. A one way ANCOVA test is used for reaction times to determine if the learning rate is significant.

ANCOVA tests allow us to compare the average scores of the PHL group and the control group. ANCOVA tests have been utilized for drug trials and other experiments where there are two or more test moments and at least two groups that have different conditions. The same test was done but using the median response times of both groups. There have been arguments made for using median response times instead of average response times to get more reliable outcomes because outliers are eliminated automatically (28)

Error rates were compared separately from the mean reaction times. For each participant the errors were added up for the pre test and the post test. A VST file containing the errors of each participants of both groups was loaded into SPS. A Non-parametric one way ANCOVA test was used to compare the error rates of the PHL group to the control group. This was done because the error rates did not prove to be normally distributed, in which case the Non-parametric ANCOVA is the preferred statistical model (28).

For both the reaction times and the error rates, basic statistical analysis like finding standard deviations were also done using SPSS to gain further insight into the results. Because this experiment deals with both errors and reaction times, we also wanted to look how these compared to each other within subject. There have been studies into which type of statistical analysis can be used to account for the speed-accuracy trade-off. The BIS analysis introduced by Liesefeld can account for these, so we included an analysis using this method (29). Finally, we compared both groups performance in the distraction task using basic statistical analysis.

4 Results

4.1 Reaction time

4.1.1 Pre test reaction times

The means of the reaction times for both groups in the pre test were comparable. The mean of the PHL group was 0.656249 while the mean of the control group was 0.686738. Trimming the mean by 5% did not change the outcomes (0.656453 for PHL versus 0.680529 for control). The median reaction times amounted to 0.639171 for the PHL group and 0.645371 for the control group. The standard deviation of the Control group was more than twice as high as that of the PHL group (0.138684 for control versus 0.059099 for PHL). The variance was also way higher, 0.019233 for control versus 0.003493 for PHL. In figure 4 we can see that although the means are very close together, other factors differ.

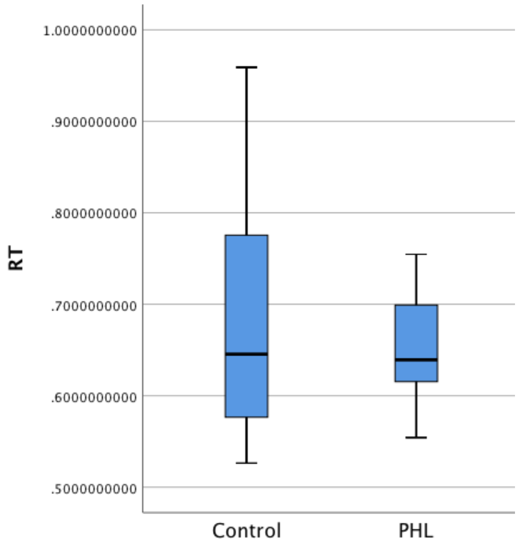


fig.5: Pre test reaction times

4.1.2 Post test reaction times

The means of the reaction times in both groups were again comparable, however, there were some effects on the median reaction time. The mean of the PHL group was in this case 0.600831 while the mean of the control group was 0.634001. The reaction time of the PHL group was 0.590123 while the median reaction time of the control group saw less of a change, amounting to 0.626792. The standard deviations of both groups became smaller, but held the same proportions (0.045737 for PHL while 0.104927 for control). Although the boxplot in figure 5 looks roughly the same, we see that the median of the PHL group went under the 600

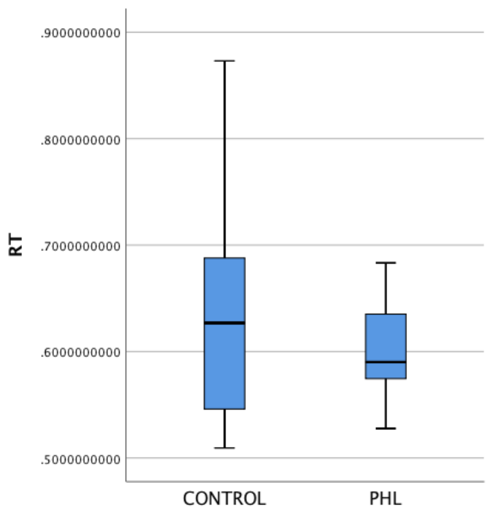


fig.6: Post test reaction times

milliseconds mark and that the variance became even smaller for the PHL group.

4.1.3 ANCOVA analysis of reaction times

As can been seen from figure 6 the average reaction times in the PHL group did decrease more than those of the control group. However, according to the ANCOVA test, these results were not significant. The mean learning rate for the PHL group was 0.055418 while that of the control group was 0.052737. As seen in Table 1 in the significance column, the P value of the 'Groups' variable is 0.409, which is not significant.

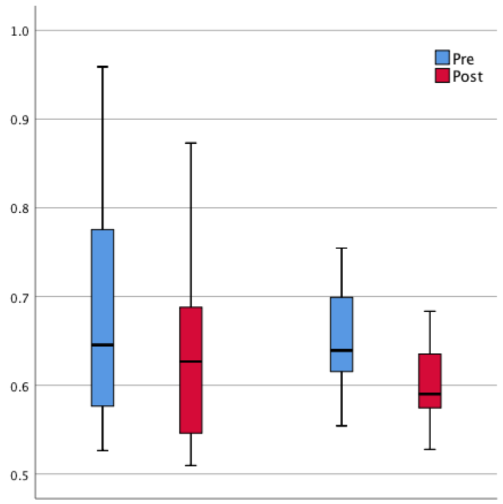


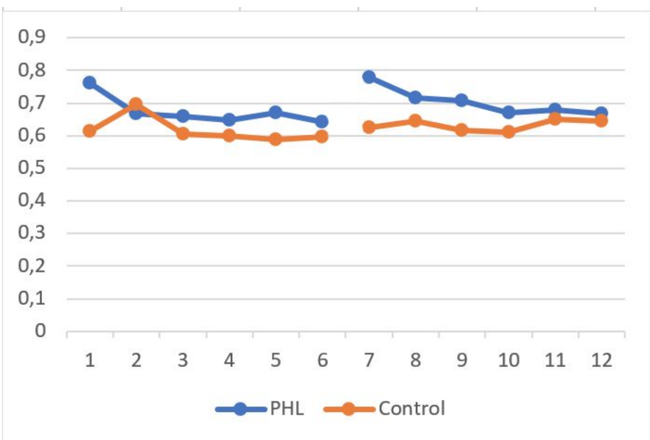
fig.7: Pre and post test scores of both groups

	Type III Sum of Source Squares	DF	Mean Square	F	Sig	Partial Eta Squared
Corrected Model	.134 a	2	0.067	31.003	0	0.689
Intercept	0.027	1	0.027	12.753	0.001	0.313
Pre	0.125	1	0.125	58.055	0	0.675
Groups	0.002	1	0.002	0.704	0.409	0.025
Error	0.06	28	0.002			
Total	11.991	31				
Corrected Total	0.194	30				

Table 1: ANCOVA reaction time results

4.1.3 Reaction times over time

In figure 7 we have plotted the mean reaction times of the PHL group and the control group over time. We took the means of 10 reaction trials and put these on the X axis. The first two lines are from the pre test and the second two lines are from the post test, with a white space where the participants had to play the game. The reaction times of the PHL group became



progressively shorter in the pre and post trials. Those of the control group stayed relatively unchanged.

fig.8: Over time plotting of reaction times per 10 trials

4.2 Error rate

4.2.1 Pre test error rates

The means of errors made in both groups in the pre test were similar, with the PHL group making a bit more mistakes. The mean of the PHL group was 1.933333 errors while the control group had a mean of 1.769231 erros. Both groups had a median amount of 2 errors. The standard deviation of both groups was also similar. The standard deviation of the PHL group was 1.222799 while that of the control group was 1.235168. The control group showed slightly more variance.

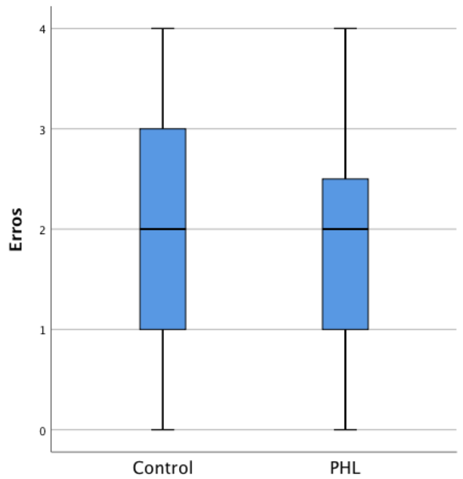


fig.9: Pre test error rates

4.2.2 Post test error rates

The means of the errors of the PHL group lowered by half while those of the control group stayed similar. The mean error rate of the PHL group was 1.066667 while the control group had a mean error rate of 1.538462. The range of the PHL group was also lower than that of the control group. None of the PHL participants made more than 3 mistakes in this phase while control group did. The standard deviation of the control group was again bigger than that of the PHL group (1.330124 for the control group and 0.883715 for the PHL group). Finally, the median amount of errors of the PHL group was 1, while that of the control group was 2.

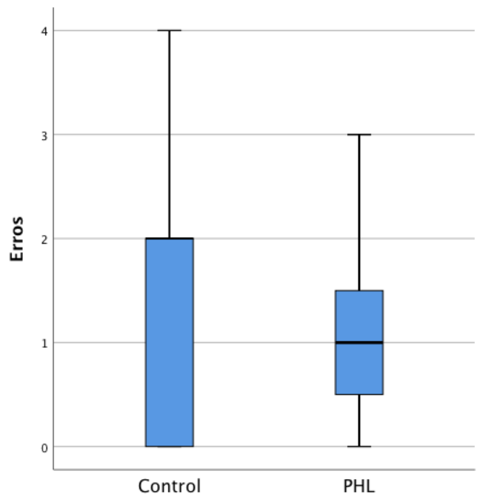
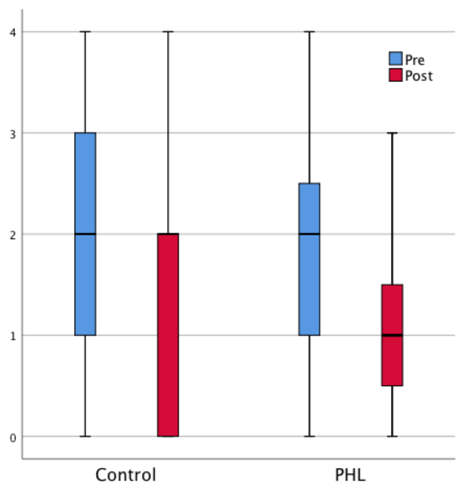


fig.10: Post test error rates

4.2.3 Learning rate error rates

The mean learning rate of the PHL group was almost three times as high as those of the control group when it came to errors. The mean learning rate of the PHL



group amounted to 0.866667 while the mean learning rate of the control group was 0.230769. However, the ANCOVA test turned out not to be significant with a significance of 0.276447.

4.3 Combined reaction times and error rates

fig.11: Post test error rates

Bis rates were calculated using the Excell formula provided by Liesefeld et al. (29) The mean Bis rates of the pre test were 1,258055 for the PHL group and 1.12474 for the control group. The mean Bis rates for the post test were 0.401695 for the PHL group and 0.34578 for the control group. Bis rates were then compared using a final ANCOVA test. The P value of the 'Groups' variable was 0.224. Although this is better than without transforming the data, this is still not significant. The variance for the Bis rates was 0.00331 for control versus 0.05493 for PHL.

4.4 Game scores and experience of participants

The mean hiscores for the game amounted to 81.90 for PHL and 86,84 for the control group. The median of the PHL group was 80 while the median of the control group was 87. The SD of the PHL group was 32.9042 while that of the control group was 34.6983.The amounts of times the players lost a life averages out between 3.1 for the PHL group and 2.8 for the control group. The participants that were part of the PHL group had the feeling that they performed better in the post test. Some of them reported that they were more confident in the choices that they had made in the post test while not being aware of actual scores. Two participants found the vibrations to be of detrimental effect, tiring their fingers while they were not using them. They had also experienced the background visual input to be distracting while playing the game of snake.

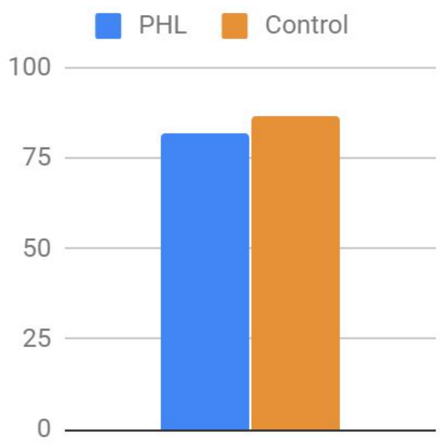


fig.12: Game scores compared

5 Discussion

When it comes to our first hypothesis we can state that there was no significant difference between the PHL group and control group in the improvement of reaction times during the experiment. Although there was slightly bigger improvement in the PHL group than in the control group results did not turn out to be significant according to the ANCOVA. One of the causes of this could be that improving reaction times with training usually takes longer to see significant changes as they tend to remain stable. We will go into this more later in the discussion.
Improvements in error rates seemed to have been more notable. While median error rates stayed the same for the control group in the pre test and the post test, the median error rate of the PHL group was cut in half in the post test, pointing at learning effects having taken place. Besides a lower median error rate, the variance and range also became smaller which can be further indication of learning having taken place. However, when we look at the results of the ANCOVA here the improvements still did not seem to be significant. The main reason for this could be that error rates were not that high to begin with, due to the mapping of the CRT task being easier to learn than expected.

As we expected, there was not much difference between results from the PHL and the control group when it came to the game they had to play. We expected this because there have been earlier studies conducted concerning how much PHL learning distracted from the task that was given to participants that concluded the same. It is important to note that both the mean reaction times and the error rates of the PHL group and the control group already started off quite different in the pre test. This could point at other influences playing a role in the experiment that were not accounted for. There could be factors like the time at which the experiments took place or any variety of influences that could have caused this.

Like stated before, there are some parts of the test design that could have been done differently to see more significant results. It seems that the reverse mapping of the keys to the stimuli was too easy to get used to. The result of this was that participants never made more than four mistakes in a test consisting of 60 trials. If we had made the mapping harder to get used to, there could have been made more mistakes and it would have been easier to see if mistakes decreased after experiencing PHL. The same goes for reaction speeds which also stayed very stable. What also could have helped is lowering the amount of pre test trials from 60 to 40 and increasing the duration of the PHL training time. As stated before, other PHL experiments use a training time of half an hour which we could not do because of time constraints. Furthermore, it would have been interesting to record which finger was used for each individual reaction trail. By doing this, we could have found out if fingers that were further apart benefited more from PHL due to vibrations being easier to distinguish.

If we look at what these results it seems at this time that PHL may have a greater effect on error rates than on reaction times. This would be interesting because most PHL experiments to date have relied on error rates as a way of measuring how PHL affected participants skill level. Although results were not significant, we still think PHL could turn out beneficial to associative motor learning with changes made to the experimental set-up. Finally, it should be stated that there were a lot of PHL experiments that did not yield the same dramatic results as those that occured in the original MIT experiment, which makes our results less of an outlier. There is still a lot to be discovered within this subject.

(1) Marchal-Crespo, L., van Raai, M., Rauter, G., Wolf, P., & Riener, R. (2013). The effect of haptic guidance and visual feedback on learning a complex tennis task. Experimental brain research, 231(3), 277-291.

(2) Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic bulletin & review*, *20*(1), 21-53.

(3) Huang, Kevin & Starner, Thad & Do, Ellen & Weinberg, Gil & Kohlsdorf, Daniel & Ahlrichs, Claas & Leibrandt, Rüdiger. (2010). Mobile music touch: Mobile tactile stimulation for passive learning. Conference on Human Factors in Computing Systems - Proceedings. 2. 791-800.

(4) Caitlyn Seim-David Quigley-Thad Starner "Passive haptic learning of typing skills facilitated by wearable computers" (2014) Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14 - 2014

(5) Hikosaka, O., Nakamura, K., Sakai, K., & Nakahara, H. (2002). Central mechanisms of motor skill learning. *Current opinion in neurobiology*, *12*(2), 217-222.

(6) Kim, D., Johnson, B. J., Gillespie, R. B., & Seidler, R. D. (2014). The effect of haptic cues on motor and perceptual based implicit sequence learning. Frontiers in human neuroscience, 8, 130

(7) Marchal-Crespo, L., van Raai, M., Rauter, G., Wolf, P., & Riener, R. (2013). The effect of haptic guidance and visual feedback on learning a complex tennis task. Experimental brain research, 231(3), 277-291.

(8) Zheng, Y., & Morrell, J. B. (2010, March). A vibrotactile feedback approach to posture guidance. In *2010 IEEE haptics symposium* (pp. 351-358). IEEE.

(9) Papenfuss, J. (2013). *The effect of sequential motor learning on cognitive control* (Bachelor's thesis, University of Twente).

(10) Anderson, J. R., & Bower, G. H. (2014). *Human associative memory*. Psychology press.

(11) Newell, F. N., Woods, A. T., Mernagh, M., & Bülthoff, H. H. (2005). Visual, haptic and crossmodal recognition of scenes. Experimental Brain Research, 161(2), 233-242.

(12) Tappeiner, H. W., Klatzky, R. L., Unger, B., & Hollis, R. (2009, March). Good vibrations: Asymmetric vibrations for directional haptic cues. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 285-289). IEEE.

(13) Powell, D., & O'Malley, M. K. (2012). The task-dependent efficacy of shared-control haptic guidance paradigms. *IEEE transactions on haptics*, *5*(3), 208-219.

(14) Powell, D., & O'Malley, M. K. (2012). The task-dependent efficacy of shared-control haptic guidance paradigms. *IEEE transactions on haptics*, *5*(3), 208-219.

(15) C. Zukin and R. Snyder. Passive learning: When the media environment is the message. The Public Opinion Quarterly, Oxford University Press, 48(3):pp. 629–638, 1984.

(16) Seim, C., Reynolds-Haertle, S., Srinivas, S., & Starner, T. (2016, September). Tactile taps teach rhythmic text entry: passive haptic learning of morse code. In Proceedings of the 2016 ACM International Symposium on Wearable Computers(pp. 164-171). ACM.

(17) Seim, C., Chandler, J., DesPortes, K., Dhingra, S., Park, M., & Starner, T. (2014, September). Passive haptic learning of Braille typing. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers*(pp. 111-118). ACM.

(18) Teichner, W. H., & Krebs, M. J. (1974). Laws of visual choice reaction time. Psychological review, 81(1), 75.

(19) Smith, E. E. (1968). Choice reaction time: An analysis of the major theoretical positions. *Psychological Bulletin, 69*(2), 77-110

(20) Mori, S., Ohtani, Y., & Imanaka, K. (2002). Reaction times and anticipatory skills of karate athletes. *Human movement science*, *21*(2), 213-230.

(21) Mowbray, G. H., & Rhoades, M. V. (1959). On the reduction of choice reaction times with practice. Quarterly Journal of Experimental Psychology, 11(1), 16-23.

(22) Pashler, H., & Baylis, G. C. (1991). Procedural learning: I. Locus of practice effects in speeded choice tasks. Journal of Experimental Psychology: Learning, Memory, and Cognition, 17(1), 20-32.

(23) Greg Anson, J. (1982). Memory drum theory: Alternative tests and explanations for the complexity effects on simple reaction time. Journal of Motor Behavior, 14(3), 228-246.

(24) Simon, J. R. (1988). A ‘priming’ effect in a choice reaction time task. Acta psychologica, 69(1), 45-60.

(25) Teichner, W. H., & Krebs, M. J. (1974). Laws of visual choice reaction time. Psychological review, 81(1), 75.

(26) Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological bulletin*, *114*(3), 510.

(27) A. Lassagne, A. Kemeny, J. Posselt and F. Merienne, "Performance Evaluation of Passive Haptic Feedback for Tactile HMI Design in CAVEs," in IEEE Transactions on Haptics, vol. 11, no. 1, pp. 119-127, 1 Jan.-March 2018.

(28) Whelan, R. (2008). Effective analysis of reaction time data. The Psychological Record, 58(3), 475-482.

(29) Liesefeld, H. R., & Janczyk, M. (2019). Combining speed and accuracy to control for speed-accuracy trade-offs. *Behavior research methods*, *51*(1), 40-60.