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An approach to human motor skill training for uniform group performance

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ABSTRACT

Prior research has focused on designing training approaches for novice operators to support maximum motor skill development. However, in production operations, workers must be trained to uniform performance levels to prevent ‘bottlenecks’ or work-in-process inventory accumulation. This study introduces a new approach to support assignment of training protocols to operators to achieve comparable levels of motor performance. Thirty-six participants performed a computer-based motor test. Based on performance classification results, each participant was assigned to a specific haptic virtual reality training condition. Results revealed participants identified as ‘medium’ or ‘low’ performers achieved levels of motor performance comparable to ‘high’ performers through 1-h training.

Relevance to Industry: Findings can be applied to operator training in manual assembly operations, promoting a group of novice workers to achieve uniform performance levels and mitigating production bottlenecks.

1. Introduction

During the past decade, the application of automation technology and robotics in manufacturing operations has expanded dramatically. However, manual work is still necessary for a variety of assembly operations, especially for customized products in small to medium batches (Alzuheri et al., 2010; Hamrol et al., 2011). If operators assigned to assembly line fail to perform standards, the productivity and efficiency of an entire line can be compromised (Vazquez and Resnick, 1997). Although human operators provide advantages of high flexibility, adaptability and creativity, they have limitations in physical and cognitive capabilities. To overcome such limitations, proper training should be provided for assembly line operators prior to assignment to actual production operations.

1.1. Manual assembly training methods

Manual assembly tasks usually require manipulation and joining of parts to form a whole product. Such tasks not only require a decent level of human motor skill, but involve higher order cognitive processing, such as understanding and memorizing procedural information, planning, recalling, and decision making (Duan et al., 2010). Conventional manual assembly training methods typically assign a group of operators to the same training condition and motivate operators to achieve their own highest skill level. Assembly skills were conveyed to novice operators through instruction manuals or tutorial videos (Gutiérrez et al., 2010; Srimathveeravalli et al., 2005). However, such training methods are not efficient due to limited work time schedules, expert availability or cost constraints. With technological advances in computer hardware and user interfaces, virtual reality (VR)-based training systems and educational software have been developed as complements or alternatives to traditional training methods (Dwivedi et al., 2018; Srimathveeravalli et al., 2005; Woll et al., 2011). These systems provided innovative ways of delivering assembly training programs, which allow for (virtual) hands-on practice within a simulated environment. However, the existence of individual differences among novice operators prior to any training has often been ignored in such methods. Consequently, uniform training of operators has generated groups with imbalanced performance. Recently, it has been suggested that production lines should be balanced to achieve higher production rates with reduced idle time (Nee et al., 2012), meaning that all operators should have comparable skill levels in completing manual production tasks. Therefore, worker differences in terms of skill and working speed must be taken into account when designing proper training methods (Altuger and Chassapis, 2010; van der Zee and Slomp, 2005).

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1.2. Motor skill training protocols

Singer (1980) defined motor skill as "the ability to execute a movement in an optimal fashion, or an activity of a person involving a single [movement] or a group of movements performed with a high degree of precision and accuracy". To assist training of operator motor skills, a variety of modalities of presentation have been suggested and developed. Initially, motor skill training was focused on visual cues (e.g., Todorov et al., 1997); however, with development of haptic devices and VR training simulations, researchers found advantages of haptic guidance for perceptual-motor skill training (e.g., Vo et al., 2009).

To reduce worker differences in task performance, it is necessary to identify the motor skill level of each operator prior to training such that proper protocols can be applied for consistent group skill. Several studies have found that performance in some simple skill tasks (e.g., target tracking, object manipulation) could be a strong predictor of skill level in more complex tasks (e.g., manual assembly). For example, Chase and Casali (1995) proposed an approach to map user performance in a basic functional hand skill test to a complex functional activity with a cursor-control device. This mapping provided a basis for device selection for the user. Ultimately, it was expected that clinicians could administer a series of 'generic' manual manipulation or dexterity tests and would be able to predict performance in any number of functional activities using different devices. In an earlier phase of the present study (Ma and Kaber, 2016), 21 participants were recruited for computer-based motor test performance along with completion of a standardized psychomotor test (in physical form). A statistics-based model was developed to classify participant motor skill level using a set of features based on kinematic parameters generated through the computerized motor test. The model was verified with an accuracy of 98% in cross-validation. The results were extended to predict performance levels in more complex tasks or real-world work for a specific operator.

1.3. Training systems with haptic feedback

In order to overcome performance gaps between novice and expert operators, it is necessary to deliver protocols with different training effects. Prior studies have found advantages of VR in presenting assembly training tasks with high degrees of flexibility and variety (Bhatti et al., 2008; Gutiérrez et al., 2010; Vo et al., 2009). Among various VR systems, those integrating haptic features (sense of contact with force at an object) led to the greatest effect of tactile feedback on operator performance (Feygin et al., 2002; Wang et al., 2006). Haptic cues are commonly presented to participants in the form of force assistance. However, some studies have observed a potential detrimental effect of consistent haptic guidance in skill development due to over-reliance during training (Li et al., 2009; O'Malley et al., 2006). For example, Bell and Kozlowski (2002) proposed a performance-based adaptive haptic guidance scheme. The adaptive guidance was designed to augment self-regulation in learning and was tailored to meet differing needs of individual trainees. The guidance scheme yielded significant improvements in acquiring basic and strategic knowledge and developing performance skills as compared to constant haptic feedback. In our previous study (Ma et al., 2017), we found that consistent haptic guidance led to participant over-reliance on training aids, degrading training effects due to loss of motivation for independent skills development and task completion. In contrast, VR training with haptic disturbance feedback produced significantly greater effects in terms of promoting motor skill learning. Experimental results of Lee and Choi (2010) also revealed that participants receiving training with haptic disturbances (resistive force or noise-like force) performed significantly better in a skill retention test as compared to those completing training under a consistent haptic guidance condition (with test scores of ~19% and ~31% higher for resistive force or noise-like force, respectively). These two types of haptic disturbances were also shown to outperform resistive force feedback with retention test scores being ~13% higher, yet not statistically different. More recently, Lee and Choi (2014) found advantages of progressive haptic guidance (i.e., the amount of guidance is decreased over the course of training) and hybrid haptic assistance (i.e., a combination of haptic guidance and disturbance) over no assistance and haptic disturbances (alone) for immediate retention of learned motor skills.

The objective of the present study was to identify appropriate protocols for effective motor skill training to achieve desired performance levels and to verify the accuracy of a classification model using a more complex task. VR-based training conditions were developed with haptic cues presented as guidance or disturbances. Participants were assigned to a specific training condition based on the results motor skill classification prior to task training. It was expected that participants would develop desired levels of improvement in motor task performance through matching of skill classification to training protocols. Assessment of this expectation represents the major contribution of the present research. More specifically, this study provided answers to the following research questions:

1) Can training on a simple skill task predict performance in more complex assembly tasks?
2) In a VR-based training simulation, what type of haptic feedback is most effective for motor skill development?
3) To what extent can matching of VR-based haptic features to motor skill development needs lead to changes in operator assembly task performance?

2. Method

2.1. Participants

Thirty-six individuals (25 males, 11 females, age: $M = 24.4$ yrs, $SD = 5.8$) from both university and off-campus population were recruited for this study. The sample size was calculated based on pilot test data (response means for experiment conditions and variance) and a Type I error of 0.05 and Type II error of 0.2. Inclusion criteria included right-handedness with 20/20 vision or corrected vision. In addition, participants were required to be in good health and to be able to follow experiment instructions for task performance. Any participant with current or chronic wrist disorders (e.g., carpal tunnel syndrome) was excluded. All inclusion criteria were verified by an online questionnaire administered in advance of participants visiting the research lab. The North Carolina State University Institutional Review Board (IRB) approved the experiment protocol and all participants signed an informed consent before any experimental procedures.

2.2. Apparatus

VR simulations of a custom dice manipulation task and the Block Design (BD) task (The Psychological Corporation, 1997) were presented to participants on a PC integrated with a stereoscopic display using an NVIDIA® 3D VisionTM Kit, including 3D goggles and an emitter (see Fig. 1). Stereoscopic rendering of the task simulation was facilitated by an OpenGL quad-buffered stereo, high-performance video card (NVIDIA® QuadroTM). A SensAble Technologies Phantom Omni® Haptic Device was provided as the haptic control interface. The Omni included a boom-mounted stylus that supported 6 DOFs movement and 3 DOFs force feedback. All data on participant performance with the Omni were recorded automatically by the VR simulation software.

2.3. Experimental tasks

All participants were required to complete a simple skill assessment test (i.e., the dice manipulation task), followed by the basic BD test, three training sessions (involving the BD task with haptic features), and

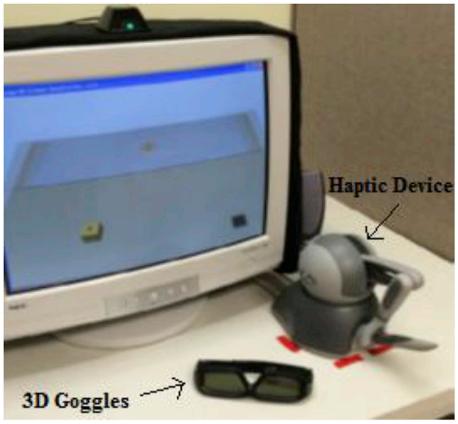

Fig. 1. Virtual reality workstation.

a final BD test. All experiment tasks were presented using the computer-based VR system as described above.

2.3.1. Dice manipulation task

A VR-based dice manipulation task was designed and prototyped in our prior study (Ma and Kaber, 2016) and was verified as a reliable tool for assessing human motor performance, as measured using the Purdue Pegboard Test (Tiffin, 1968). The task environment included a single virtual dice placed near the left-side of a virtual work surface and a square near the right-side of the work surface (see Fig. 2). A 2D image of a single side of the dice (stimulus) was presented at the top of the screen in the display area. The goal of the task was to move the dice as quickly and accurately as possible to the target square with the top surface of the dice matching the stimulus. Results of task performance were used as inputs to the skill classification model and as a basis for assigning participants to one of three motor skill groups (i.e., high, medium, or low).

2.3.2. Basic block design (BD) task

A VR version of the Wechsler Adult Intelligence Scale (WAIS; The Psychological Corporation, 1997) BD task was presented to participants. The physical form of this task involves using small wooden blocks with white and red colored sides to assemble patterns presented in a design book. This task was simulated with high fidelity in a VR application (see Fig. 3, from Clamann et al., 2013). The features of the VR-BD task included a virtual tabletop divided into two parts, including a display area and a work area. The display area presented the stimulus design pattern to be replicated by a participant. The work area was used to arrange the blocks. The work area and blocks were presented at

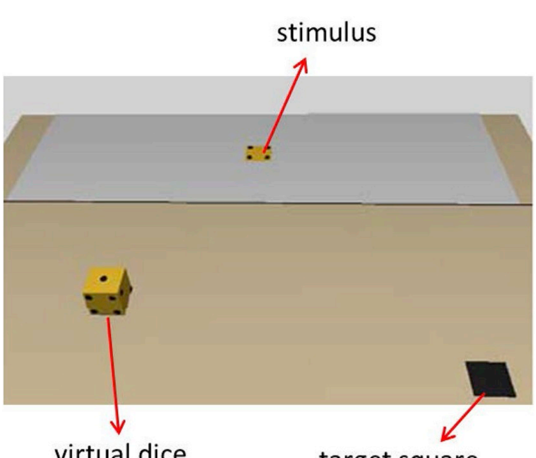

Fig. 2. Dice manipulation task.

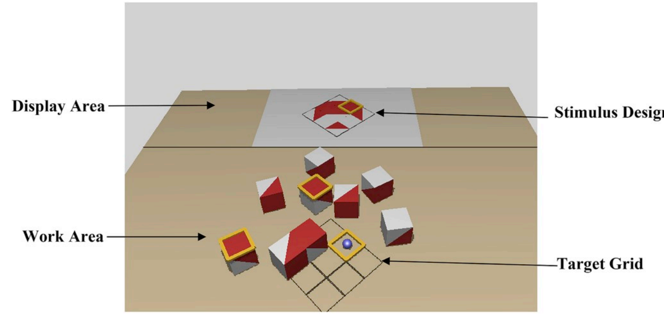

Fig. 3. Virtual block design task.

approximately 70% of actual size to allow the design pattern and workspace to be viewed on a 21-inch stereo monitor. All BDs were constructed with the aid of a target grid, which appeared as a 2 × 2 or 3 × 3 collection of squares in the work area (see Fig. 3), depending on the design stimulus. In order to reduce the potential influence of cognitive workload on participant performance, a grid was also presented over the stimulus design. In this way, participants were presented with the test solution and performance was expected to be dependent on motor skill.

2.3.3. Block design task with haptic features

Based on the general form of the BD task, different haptic features were presented during each training condition (see below for detailed descriptions) offering different levels of assistance to participants according to their skill classification results. In addition, the stimulus designs used in the training were based on the Wechsler Abbreviated Scale for Intelligence (WASI; The Psychological Corporation, 1999). This version of the BD task was identical to the WAIS version except for the design patterns. As in the basic BD task, a grid was superimposed on the stimulus design patterns during each trial to reveal the solution to construction for participants.

2.4. Procedure

Upon completion of the informed consent form, participants began the experiment with 40 trials of the dice manipulation task. They were permitted a short break and then presented with the basic BD task. Participants were asked to complete the design pattern assembly tasks as quickly and accurately as possible during each trial. For the baseline BD test, WAIS Designs 9–14 were used, which are the most complex designs as part of the set of 14 designs.

Based on their motor performance in the dice manipulation task, participants were classified (Ma and Kaber, 2016) and assigned to one of the three haptic training conditions. All participants were required to complete three training sessions of the VR-BD task with the additional haptic features. Each session included six trials with different stimulus design patterns. An earlier experiment by Kaber et al. (2014), involving training in the VR-BD task, revealed that participants exhibited signs of fatigue after 5–6 consecutive trials when using their non-dominant hand. It was suggested that better training could be achieved by providing several sessions with short breaks in between. Moreover, Clamann et al. (2013) showed that participants were able to reach asymptotic performance in the VR-BD task after 3–5 training sessions using the non-dominant hand. Since participants were required to use the dominant hand in the present research, it was assumed that three sessions would be sufficient to promote participant asymptotic performance without signs of fatigue. The 6 trials in each training session involved the construction of WASI Designs 8–13 (The Psychological Corporation, 1999), as presented in random order. These designs were selected as they are the most complex among the set of 13 WASI designs. Between training sessions, participants were asked to take a break for at least 5 min to further prevent the potential wrist and forearm fatigue.

Following completion of the training, participants were required to complete an additional basic VR-BD test, identical to the one taken before receiving the training. Once again, WAIS Designs 9–14 were used in the post-test. The entire experiment lasted for about 100 min. Throughout entire experiment, participants were not provided with any information on their design completion time so as to avoid temporal stress/workload.

2.5. Independent variables

The independent variable for this study was the training condition assigned to participants. There were three types of training based on the haptic feature presented during the VR-BD task, including consistent haptic guidance (CG), resistive haptic force feedback (RF), and haptic disturbances with random force feedback (HD).

2.5.1. CG condition

In the CG condition, the haptic device presented an assisting force to facilitate accurate participant hand movement during block manipulation. A 'snap force' with a consistent magnitude of 0.5 N was presented with a direction from the current cursor position to the center of a target square location in a design pattern.

2.5.2. RF condition

In the RF condition, resistive forces were presented to inhibit participant hand movements to correctly orient and locate blocks for design pattern reconstruction. The resistive force was also presented with a consistent magnitude of 0.5 N. Different from the CG condition, this force was directed away from the center of a target location in a design pattern and towards the current cursor position.

2.5.3. HD condition

In the HD condition, random or 'noise-like' forces were presented to disturb participant performance. The forces were randomly generated between 0 and 0.6 N and presented at a random directions with a frequency between 0 and 0.5 Hz. Lee and Choi's (2010) study suggested that when exposed to the noise-like force with a regular frequency, participants were likely to only perform between disturbances and pause when the noise force was present. Therefore, to avoid participant prediction of the time when a disturbance would occur, the random force frequency was used. The magnitude of the forces and the frequency were generated by RAND() functions in C++. Applying these methods, each force persisted for 1 s each time it was presented.

2.6. Training condition assignment

Based on the findings of Ma et al. (2017) and Lee and Choi (2010), participants demonstrating an initial high performance in the dice testing application were assigned to the CG training condition. For participants demonstrating an initial low performance, three training sessions were conducted with the haptic device presenting random force-feedback; i.e., the HD condition. For participants demonstrating a transitional or moderate skill level in the dice test, the RF training condition was provided.

2.7. Dependent variables

The time needed to complete the baseline and final BD tests were the primary response measures for this experiment. The completion time of all BD task trials was automatically recorded by the VR-BD program. Beyond this, participant learning percentage (k-value) for each training condition was calculated based on the trend of BD task completion time across the three training sessions (see Equation (1); Konz and Johnson, 2004):

$$Y_n = Y_1 \times n^b \tag{1}$$

where Y_n is the task performance in the nth trial. Taking the natural log of both sides of the equation, the formula becomes:

$$\ln(Y_n) = \ln(Y_1) + b \times \ln(n) \tag{2}$$

After solving for the coefficient b, the learning parameter, by using linear regression, the learning percentage (k) can be calculated with Equation (3).

$$k = 2^b \tag{3}$$

The set of k-values was used as a secondary measurement to explore potential learning and rate of improvement in task performance.

2.8. Hypotheses

Based on our review of prior research, the following hypotheses (H) were formulated for the present motor skill experiment:

H1. Participant performance in the simple dice manipulation was expected to be predictive of performance in the more complex BD task (Chase and Casali, 1995).

H2. RF and HD training conditions were expected to significantly improve participant performance in the final post-training BD test, while the CG condition was not expected to produce significant improvements in post-training tests (Lee and Choi, 2010).

H3. Matching of the haptic feature conditions in VR task training to participant motor skill classification was expected to produce comparable levels of BD/assembly task performance among the various skill groups.

2.9. Data analysis

A one-way ANOVA test was performed to identify any performance differences among the three training condition groups in completing the baseline and final BD tests. Tukey's Honestly Significant Difference (HSD) method was applied to further identify differences between pairs of skill groups. In addition, paired t-tests were applied to compare participant performance between the baseline and final VR-BD tests within each training group (i.e., CG, RF, HD). A significance level of $\alpha = 0.05$ was used as the statistical criterion for this study. All graphs of response measures present untransformed mean values at the top of bars. In addition, all error bars represent 95% confidence intervals.

3. Results

Applying the classification algorithm developed in our previous study (Ma and Kaber, 2016), and using dice manipulation task performance measures as inputs, 36 participants were classified as 6 high performers (H), 17 as moderate performers (M), and 13 as low performers (L). For each participant, the completion times for all six trials as part of a training session was summed-up for further analysis. Table 1 presents a summary of the descriptive statistics for BD task session completion time.

3.1. Within-group comparison of baseline and final test performance

Fig. 4 presents the BD baseline and final test session completion times for the three training groups making use of the VR workstation and Omni interface. Results revealed that all three training conditions produced improvements in final test performance, as compared to the baseline test.

Paired t-tests were conducted to compare within-group differences between baseline and final test results. Table 2 presents a summary of the t-test results, including t-statistics, p-values, and statistical power. All t-tests were one-tailed and assumed that performance would improve (i.e., a reduction in task completion time) in the final test. Results revealed

Table 1
Task completion time descriptive statistics.

Motor Skill Group	N	Task Completion Time (sec) (mean ± SD) Baseline	Training 1	Training 2	Training 3	Final
High	6	511.3 ± 45.0	371.8 ± 78.6	322.3 ± 62.7	304.7 ± 47.6	312.3 ± 36.7
Medium	17	657.1 ± 163.6	633.1 ± 146.3	559.1 ± 139.1	502.2 ± 140.9	435.5 ± 102.7
Low	13	830.7 ± 231.1	871.9 ± 289.9	678.1 ± 204.4	650.2 ± 192.4	479.2 ± 141.2

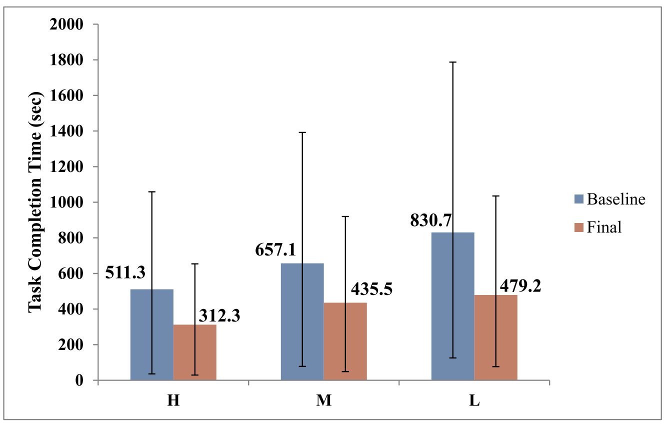

Fig. 4. Comparison of performance in baseline and final BD tests. Error bars indicate 95% confidence intervals.

a significant decrease in completion time from baseline to final test for all three condition groups.

3.2. *Between-group comparison of baseline and final test performance*

To assess between-group differences in terms of the baseline and final VR-BD test completion time, one-way ANOVA tests were conducted. The statistical results are summarized in Table 3, including *F*-values, overall *p*-values, statistical power, and *p*-values for Tukey's pairwise group comparisons. For the baseline test, there were significant differences among the three groups. Low performers were found to spend significantly longer time than high and medium performers in completing the test. However, there was no significant difference between medium and high performers in terms of task completion time. In addition, there was a significant between-group difference in terms of final test performance time. Low performers produced significantly longer BD completion times as compared to high performers.

An additional one-way ANOVA was conducted to compare the final post-training test performance of medium and low performers with the initial performance of high performers (see Fig. 4). Results did not reveal any significant difference among the three groups ($F(2, 33) = 1.19$, $p = .316$, $1 - \beta = 0.22$). Therefore, through the three training sessions, medium and low performers were successfully brought to a similar level of motor skill, as compared to the high performers, before exposure to any training.

Table 2
Summary of paired *t*-test results.

Motor Skill Group	Paired *t*-test
High	$t(5) = 14.28$, $p < .001$*, $1\text{-}\beta = 1$
Medium	$t(16) = 7.75$, $p < .001$*, $1\text{-}\beta = 1$
Low	$t(12) = 11.14$, $p < .001$*, $1\text{-}\beta = 1$

Table 3
Summary of one-way ANOVA and Tukey HSD results.

	One-way ANOVA	Tukey's HSD
Baseline	$F(2, 33) = 7.13$, $p = .002$*, $1\text{-}\beta = .84$	L – H: $p = .003$* L – M: $p = .036$* M – H: $p = .22$
Final	$F(2, 33) = 4.58$, $p = .018$*, $1\text{-}\beta = .68$	L – H: $p = .013$* L – M: $p = .546$ M – H: $p = .068$

Note: L = Low; M = Medium; H=High.

3.3. *Learning percentage in BD training*

The trend of performance for the three skill classification groups in completing BD training sessions with different haptic features is presented in Fig. 5. By fitting the training session completion time (i.e., sum of six trials in the same session) to the learning model, a learning percentage was calculated for each participant. To further explore the learning potential of participants through the training, learning percentages (*k*-value) were calculated for each group or haptic feature condition (Table 4). Results did not reveal statistically significant differences between the groups ($F(2, 33) = 0.59$, $p = .56$, $1 - \beta = 0.15$). However, on average, low performers were found to have the lowest learning percentage (84.0%), indicating the fastest learning potential with the haptic disturbances (HD) condition.

4. Discussion

The first hypothesis (H1) stated that performance measures obtained in a simple skill task (VR dice manipulation) could be used to predict performance levels in a more complex motor assembly task. This hypothesis was supported by the results of the experiment. Statistical analysis of performance in the baseline VR-BD simulation revealed significant differences ($p = .002$) among the three groups of participants (low, medium and high performers). Findings suggest that performance of the dice manipulation task could serve as a reference for predicting motor skill in assembly tasks. These results are in line with the findings of Chase and Casali (1995), who mapped users' performance on a basic functional hand skill test to a complex functional activity. In addition, our results further verified the capability of the classification model (Ma and Kaber, 2016) for identifying individual motor skill levels.

The second hypothesis (H2) posited that only RF and HD training conditions would significantly improve participant performance in the final assembly task test. This hypothesis was partially supported by the data. Within-group comparisons of baseline vs. post-training (VR-BD) test performance revealed highly significant differences for all three

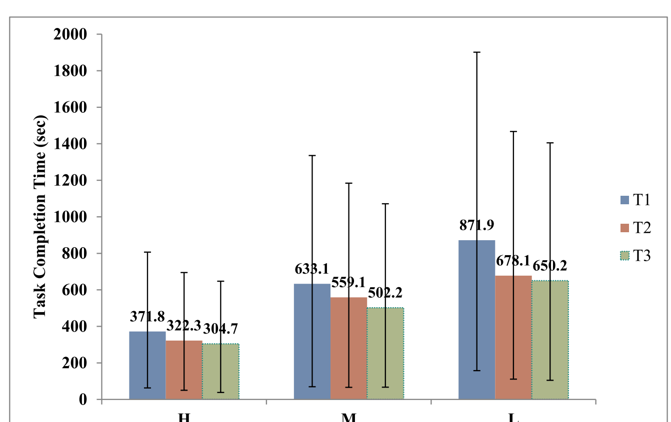

Fig. 5. Performance time in BD training. Error bars indicate 95% confidence intervals.

Table 4
Learning percentage descriptive statistics.

Motor Skill Group	Learning percentage (mean ± SD)
High	88.6 ± 6.5
Medium	86.6 ± 7.5
Low	84.0 ± 12.1

training groups ($p < .001$). As expected, the two conditions involving haptic disturbances (HD, RF) revealed significant effects on improving participant motor performance. Although prior studies have shown VR training with haptic guidance (CG) to potentially degrade motor task learning, as compared to the use of haptic disturbances (HD/RF), high performers in this study still achieved significant improvement in motor skill with guidance (CG). It is possible that specific designs of haptic guidance conditions (e.g., trajectory tracking, force boundaries, target attraction forces) may vary in terms of motor control learning effects. This observation is supported by contradictory results of some prior studies. For example, Feygin et al. (2002), O'Malley et al. (2006), Lee and Choi (2010), and Powell and O'Malley (2012) found positive training results while Edwards et al. (2004), Li et al. (2009), and Lee and Choi (2014) observed negative or no effects using different haptic training conditions.

The third hypothesis (H3) stated that training protocols, presenting specific haptic features, could be designed and selected to bring participants to desired and/or comparable levels of motor skill. Results were in partial support of this hypothesis. During training, those participants classified as low performers were assigned to the most challenging VR haptic feature condition (i.e., HD) with the expectation of producing the greatest improvements in motor skill test performance. Similarly, those participants classified as high performers were assigned to the least challenging VR haptic feature condition (i.e., CG) with the expectation of producing the lowest degree of improvement in motor skill test performance. Medium performers were assigned to what was considered as a moderately challenging haptic feature condition (i.e., RF). Participants initially classified as low and medium performers revealed significant differences in baseline motor test performance ($p =$ .036). They demonstrated comparable levels of motor skill based on VR-BD test performance ($p = .546$), after exposure to equivalent amounts of training. Furthermore, there was no significant difference between the medium and high performer post-training test performance results ($p =$ .068) based on prescription of specific haptic training conditions for an initial skill classification. However, there was a significant gap between low performer post-training test performance and high performer outcomes ($p = .013$).

Although assigned to the least challenging training condition (CG), high performers still demonstrated significant improvements in motor skills. It is likely that the performance gap between low and high performers was caused by 'overtraining' of the high performers. This situation was verified by no significant difference between the final post-training test performance of medium and low performers with the initial performance of high performers. If the high performers were not exposed to any haptic VR training, it is likely that the post-test results would have been comparable for all groups. Therefore, we can assume that by reducing the amount of training for high performers, comparable levels of BD task performance among different skill groups could be achieved. In general, the problem of specific training condition prescription for operators, based on motor skill classification is complex and specific haptic VR features should be associated with values of specific motor performance features extracted from initial classification task performance.

The findings of this study provide a potential solution for applying "lean concepts" to manual assembly production lines considering individual differences among operators. Variability in human operator performance may make achieving the application of lean production challenging (Altuger and Chassapis, 2010; Hamrol et al., 2011). To solve this problem, many algorithms and mathematical models have been developed to optimize operator work scheduling and production plans. One common assumption of these methods is that operators are viewed as interchangeable, i.e., all operators have comparable skill levels in completing production tasks. However, it is more likely that this scenario is not a reality for a physical production line (van der Zee and Slomp, 2005). To address this issue, individual differences in novice operator abilities must be considered during design and selection of training systems and training tasks.

5. Conclusion

The objective of the present study was to identify appropriate protocols for effective motor skill training to achieve desired levels of performance. Three haptic-VR training protocols were designed and assigned to participants based on their identified skill levels. The specific training conditions (VR haptic features) designed for the various levels of baseline motor skill provided effective skill training to desired levels, especially for those individuals identified as moderate and low performers, in terms of motor control.

This training approach involving motor performance analysis and classification can be applied in the training of manual assembly, military tasks, or other sophisticated manual control operations requiring uniform performance levels among soldiers or operators. In a manufacturing context, this approach could potentially be used to mitigate production bottlenecks and to promote higher production rates in manual assembly operations.

5.1. Limitations

The present study had some limitations. The only aspect of the training that was manipulated through experimentation was the design of haptic guidance or challenge features in a VR environment. All other dimensions of the training regimen were held fixed across participant groups, including the timing and extent of exposure to training conditions. In addition, the stylus shape of the haptic control device applied in this study might have led to differences in performance with physical blocks in the BD task. In using the haptic device, users needed to translate the rotation of the stylus according to the orientation of the virtual blocks. This process likely increased cognitive workload, especially for low performers.

5.2. Future work

Future research should expand the current design of experiment, including manipulation of the amount of operator training, as an additional control parameter. By assigning groups of participants to all training condition combinations, the interaction between duration of training and type of training could be investigated. It is likely that some types of haptic feedback would be better suited for training specific groups of participants than others. In addition, apart from the WAIS BD test, the effectiveness of the haptic VR training for motor skill development could be verified through complimentary testing in a physical or simulated version of an assembly task. It would be worthwhile to extend the new approach to a higher level of skill training for more complex motor/control tasks.

Author statement

Wenqi Ma: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing.

David Kaber: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Supervision.

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Declaration of competing interest

There are no interests to declare.

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