Automaticity of Force Application During Simulated Brain Tumor Resection: Testing the Fitts and Posner Model

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OBJECTIVE: The Fitts and Posner model of motor learning hypothesized that with deliberate practice, learners progress through stages to an autonomous phase of motor ability. To test this model, we assessed the automaticity of neurosurgeons, senior residents, and junior residents when operating on 2 identical tumors using the NeuroVR virtual reality simulation platform.

DESIGN: Participants resected 9 identical simulated tumors on 2 occasions (total = 18 resections). These resections were separated by the removal of a variable number of tumors with different visual and haptic complexities to mirror neurosurgical practice. Consistency of force application was used as a metric to assess automaticity and was defined as applying forces 1 standard deviation above or below a specific mean force application. Amount and specific location of force application during second identical tumor resection was compared to that used for the initial tumor.

SETTING: This study was conducted at the McGill Neurosurgical Simulation Research and Training Center, Montreal Neurologic Institute and Hospital, Montreal, Canada.

PARTICIPANTS: Nine neurosurgeons, 10 senior residents, and 8 junior residents.

RESULTS: Neurosurgeons display statistically significant increased consistency of force application when compared to resident groups when results from all tumor resections were assessed. Assessing individual tumor types demonstrates significant differences between the neurosurgeon and resident groups when resecting hard stiffness similar-to-background (white) tumors and medium-stiffness tumors. No statistical difference in consistency of force application was found when junior and senior residents were compared.

CONCLUSION: "Experts" display significantly more automaticity when operating on identical simulated tumors separated by a series of different tumors using the NeuroVR platform. These results support the Fitts and Posner model of motor learning and are consistent with the concept that automaticity improves after completing residency training. The potential educational application of our findings is outlined related to neurosurgical resident training. (J Surg Ed 75:104-115. © 2018 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

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COMPETENCIES: Medical Knowledge, Practice-Based Learning and Improvement, Systems-Based Practice

INTRODUCTION

The complex term "expertise" has no exact definition relating to neurosurgical psychomotor performance; however, achieving expertise in surgical technical skills is an aspirational goal.[1-3] Understanding the multiple interacting factors resulting in the acquisition of expertise may be useful to enhance learning and maintenance of neurosurgical ability. Fitts and Posner proposed a motor skill learning model highlighting stages the learner navigates when acquiring new motor skills: cognitive, associative, and autonomous.[2,4] In the cognitive phase, the learner builds component units of the skill and consciously performs the task slowly, committing numerous errors with marked inconsistency. The performance becomes faster, more accurate, and consistent in the associative phase. In the autonomous phase, the skill becomes habitual, executed unconsciously with fluency, accuracy, and consistency of performance.[2,4-6] If this model pertains to the neurosurgical acquisition of operative skills, components of this model should be both testable and true. During training, residents should progress through the 3 phases outlined. Our group has developed and validated psychomotor metrics that objectively measure manual performance in medical students, residents, and neurosurgeons during resection of virtual reality tumors using the NeuroVR platform.[7-17,25-27] Automaticity of surgical performance encompasses many components including increased fluency, accuracy, and consistency. Our results are consistent with the model involving fluency and accuracy of manual psychomotor performance.[7,12,13] "Experts" in the autonomous stage of learning faced with similar operative pathologies should demonstrate significantly more consistency in their surgical approach. Surgical consistency could include consistency of force application, rate of tumor resection, and amount of normal tissue injury. In this study, we focused on consistency of force application as excessive force application is related to surgical error.[18] Our previous studies using virtual reality tumor resection categorized maximum force applied and sum of force used as safety metrics.[7,11] Consistency in performance is the feature that most distinguishes experts from novices.[19] The effect of consistency in sports performance is well established.[19-24] Neurosurgeons are faced with a wide variety of tumor pathologies involving multiple surgical approaches. However, similar tumors do present on different occasions and require comparable neurosurgical procedures.

One testable question posed by the Fitts and Posner model is: Are "experts" more autonomous in their operative resection when faced with identical tumors on different occasions separated by various tumor surgeries? To mirror clinical reality, we studied the virtual reality resection of 9 identical simulated brain tumors separated by the removal of a variable number of other tumors with different visual and haptic complexity. To address automaticity of operator performance, we assessed the consistency of amount and location of force applied during resection of these identical tumors by neurosurgeon and resident groups.

METHODS

Subjects

Nine board-certified and practicing neurosurgeons from 3 institutions, 10 senior (9 postgraduate year [PGY] 4-6 and 1 fellow PGY-7), and 8 junior residents (PGY 1-3) from McGill University participated in the study. The fellow had just completed neurosurgical residency, and it was considered appropriate to place this individual in the resident group as adding or excluding this individual did not change statistical results. No participant had previous experience with NeuroVR. All participants signed a consent approved by McGill University Health Center Research Board. As we have previously documented significant differences in psychomotor performance based on the ergonomics of handedness, only dominant right-handed participants were assessed in this study.[12]

NeuroVR Simulator

The previously described NeuroVR (formerly NeuroTouch) platform with haptic feedback was used for this study.[7-17,25-30] Tumor resection was performed using a simulated ultrasonic aspirator held in the right hand (Fig. 1A).

Simulation Scenarios

To address the study question, the scenario employed involved resection of 9 identical simulated brain tumors on 2 separate occasions (18 procedures) separated by removal of tumors with different complexities (Fig. 1B).[9-12] The simulated operative procedure used can be seen in electronic supplemental material, video 1 in a previous publication.[11] To prevent the operator from predicting the appearance of the next identical tumor in the resection sequence, the 2 identical ellipsoidal tumors were separated by between 4 and 12 different tumors (Fig. 1B-D). To maximize tumor differences, each of the 6 scenarios had 3 tumors of varying complexities involving color (black, glioma-like, and white) and Young's modulus stiffness (3 kPa, soft; 9 kPa, medium; and 15 kPa, hard). White background with soft (3 kPa) tumor stiffness represented the surrounding

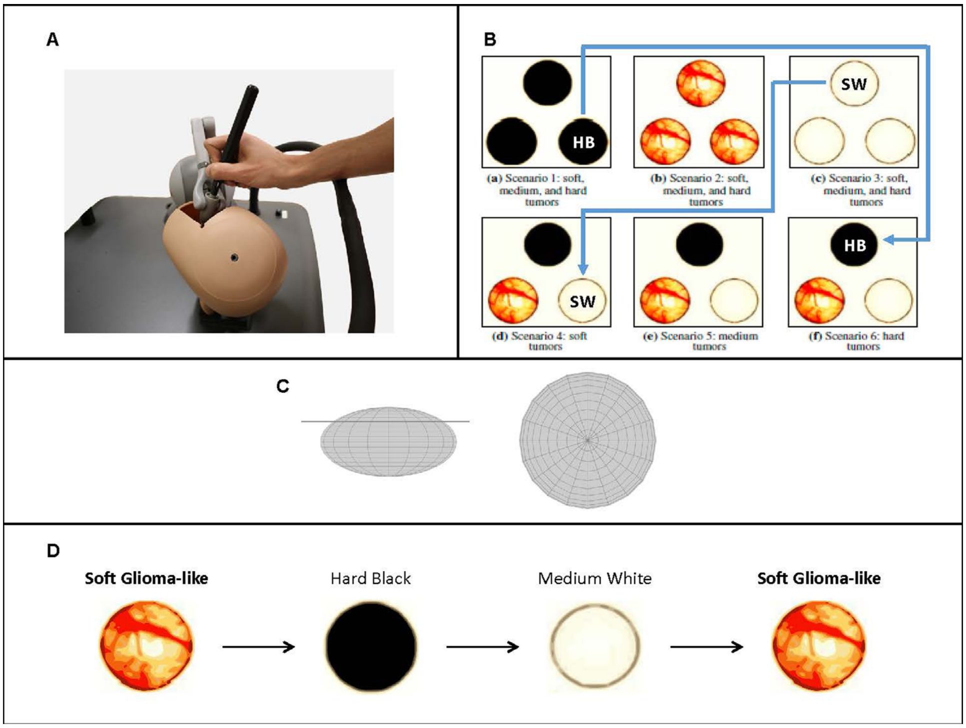

FIGURE 1. A) Operator with simulated aspirator in right hand. (B) The 6 scenarios included in the study. Tumor colors are black, glioma-like, and similar-to-background (white). Tumor stiffness is indicated for each scenario: soft, medium, and hard. Arrows indicate 2 identical tumor pairs: hard black (HB) with the largest (12), and soft white (SW) with the smallest (4), intervening tumors between them, respectively. (C) Lateral and top view of tumor. (D) Depiction of tumor resection sequence demonstrating identical tumor separated by other tumors.

"normal" white matter (Fig. 1C). Three minutes were allowed for removal of each of the 18 tumors one at a time in a predefined order (Fig. 1B) with a 1-minute mandatory rest time between each resection. The trial took 71 minutes in which 54 minutes for active tumor resection. To enhance procedure familiarity, a practice scenario was used. Data from this resection were not analyzed. Participants had no knowledge of the study purpose or the metrics used to assess performance. Each participant was instructed in verbal and written instructions that the goal of the simulation was to remove each tumor with minimal removal of the background tissue.

Defining Automaticity and Setting a Consistency Benchmark

Automaticity is the ability to do things without occupying the mind with the required low-level details; usually resulting from learning, repetition, and practice.[2] For this study, automaticity for tumor resection was defined as force application in Newtons (N) within a distinct consistency benchmark when resecting 2 simulated identical tumors. The mean and standard deviation (SD) of force application for all resected tumors were different, 0.021 ± 0.018 N for neurosurgeons, and 0.033 ± 0.021 and 0.035 ± 0.036 N for senior and junior residents, respectively, as was the mean for each individual tumor resected by each group. These variabilities in performance were accommodated by using each group's mean for all tumors and each individual tumor as each group's baseline. As consistency in performance distinguishes "experts" from "novices," we defined a consistency benchmark, as ± 1 SD (±0.018 N) of neurosurgeon group force application during resection of all 18 tumors. This encompassed all applied forces 0.018 N above and 0.018 N below the mean for that study group (Figs. 2 and 3). We explored other consistency benchmarks including using ±0.5 SD, but the results were not different from those reported. Positive variability was defined as force application above and negative variability as below this consistency benchmark range (Figs. 2 and 3). Total variability can be considered as the sum of both positive and negative variability (Figs. 2 and 3).

Analysis of Force Application

For each tumor, the total application of forces at the same location (*xy*-location) was averaged. To compare the 2 identical tumors for consistency of force application, the average force applied at each *xy*-location during first identical tumor resection (Fig. 2A) was subtracted from the average force applied at the comparable *xy*-location during the second identical tumor resection (Fig. 2B), and the difference was quantitated (Fig. 2C). Spatial representations of force difference were created and represented by 3D formats (Fig. 2D) and top view grids (Fig. 2E). These spatial representations were colored to represent locations of

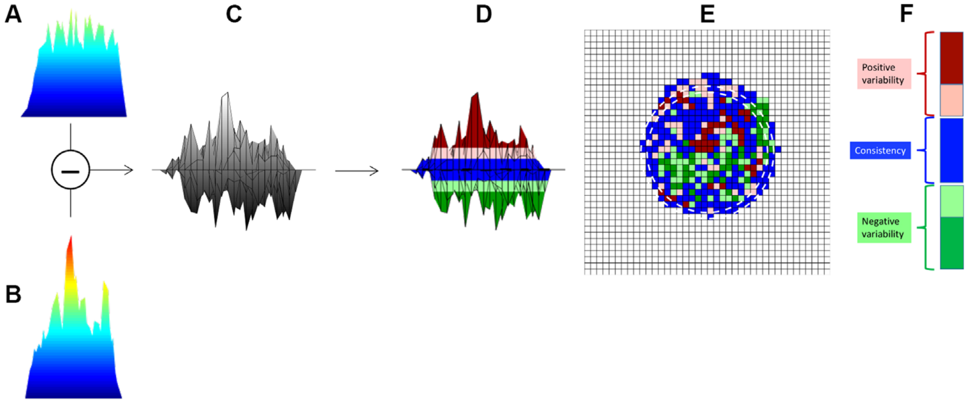

FIGURE 2. Generation of 3D formats and top view grids. (A) Force pyramid of first resected tumor. (B) Force pyramid of second resected tumor. (C) Result of subtraction of force pyramid A from force pyramid B. (D) Color assignment of results based on consistency, positive variability, and negative variability benchmarks (3D formats). (E) Color assignment of top view grid results based on consistency, positive variability, and negative variability. (F) Color map outlines consistency (blue), positive variability (red), and negative variability (green) benchmarks.

consistency and variability in performance. Psychomotor performance consistency was calculated as the area of each group's mean ± 0.018 N and is outlined in blue (Fig. 2D and E). Psychomotor performance variability was calculated as all areas >0.018 N above or below the mean value for that group and outlined in shades of red and green (Fig. 2D and E). Red colors indicate spatial areas of positive variability where the participant applied forces >0.018 and <0.036 N, and >0.036 N higher in the second compared to the first identical tumor. Green colors indicate spatial areas of negative variability where operators applied forces <0.018 and >0.036 N, and >0.036 N lower in the second compared to the first tumor (Fig. 2). Other positive and negative variability thresholds were also assessed and were not different from those reported in this article.

For each of the 9 tumor types, consistency of performance was calculated as the percentage of tumor area where the forces applied were at the mean for that group and in the defined consistency benchmark described previously. Total percentage consistency for each participant was calculated by averaging the consistencies for the 9 identical tumor types resected by that participant. The total consistency for each tumor type was assessed by averaging all consistency values for that specific tumor for all individuals in that group. Total consistency for the 9 tumors was assessed by averaging all consistency values for all 9 identical tumors for individuals in that group. Statistical comparison of consistency between groups was assessed. Positive (>0.018 and <0.036, and >0.036 N) and negative (<0.018 to <0.036, and >0.036 N) variabilities for each tumor type were also performed to verify if groups applied statistically significant higher or lower forces during the resections.

Statistical Analysis

All statistical analysis was performed using STATA version 14.0 (Stata Corp, College Station, Texas). Continuous and categorical variables were described using means and percentages, respectively. For comparison of consistency among the 3 groups, Kruskal-Wallis test was used followed by Dunn's post hoc test for pairwise comparisons. Values are represented as means ± SEM, and $p < 0.05$ was considered significant.

RESULTS

Demographics

Neurosurgeon mean age was 40.3 ± 7, senior residents 32.1 ± 3.5, and junior residents 27.3 ± 1.8. All participants were right-handed, and 15% were females. The 9 neurosurgeons had 8.4 ± 5.7 years of practice experience.

Top View Grids and 3D Formats: Consistency and Variability of Force Application

Figure 3 demonstrates examples of top view grids and 3D formats of positive, negative, and total variability of a participant resecting a soft glioma-like tumor. Top view grids provide the location in a color-coded visualization: the consistency areas (blue), the positive variability areas (red), and negative variability areas (green). The 3D formats provide additional quantitative information of location and amount of force application, consistency, and variability. Positive and negative variability 3D formats are tilted to improve visualization of the forces applied. In this example, there are few blue regions of performance consistency. Positive variability (higher forces applied) is seen in the tumor center and regions of negative variability in the lower tumor quadrants.

Consistency of Performance

When total consistency for all tumors was assessed, the neurosurgeon group showed a statistically significant higher

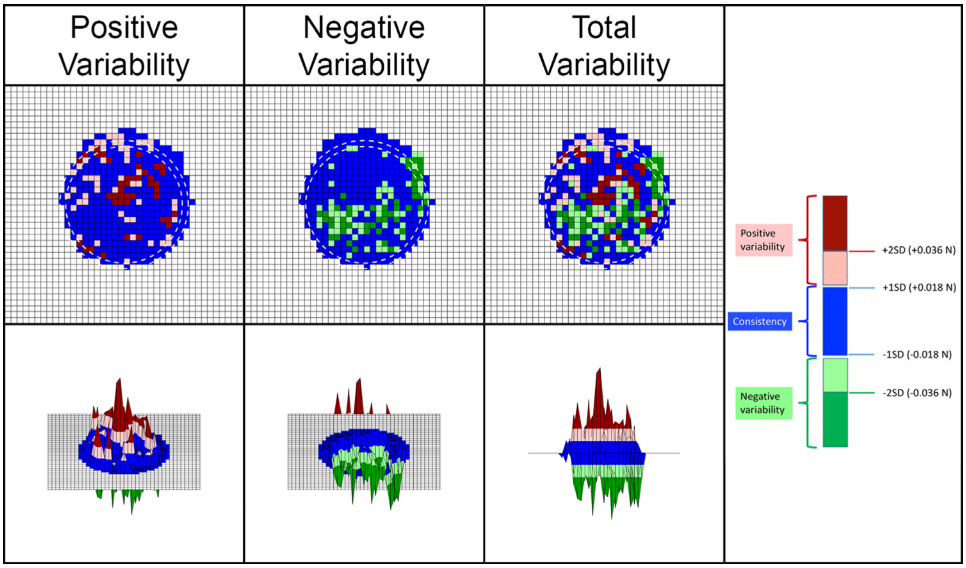

FIGURE 3. Examples of top view grids and 3D formats of positive, negative, and total variability for a participant resecting a soft glioma-like tumor. Color map outlines consistency for that particular tumor (blue), positive variability (red), and negative (green) variability benchmarks.

consistency in performance than resident groups (Fig. 4A). There was no statistically significant difference between resident groups (Fig. 4A). All individual tumor types included showed higher consistency in performance in the neurosurgeon group, and this reached statistical significance for hard stiffness white and medium-stiffness glioma-like tumors (Fig. 4B and C).

To outline if the statistically significant higher consistency in performance of neurosurgeons was related to differences in resident application of higher or lower forces, positive and negative variabilities were assessed. Figure 5A outlines the total consistency of force application for all tumor types for each group along with positive and negative variabilities. Neurosurgeons had statistically significant higher consistency of force application compared to resident groups (Fig. 5A). There was no statistically significant difference between resident groups. The positive and negative variability ranges of each group did not show statistical difference. All individual tumor types had higher consistency in performance in the neurosurgeon group, and this reached statistical significance for hard stiffness white and medium-stiffness glioma-like tumors (Fig. 5B and C). For hard stiffness white tumors, junior and senior residents applied significantly higher (total positive variability) than lower forces (total negative variability) (data not shown).

Top View Grids and 3D Formats

Hard Stiffness, White Tumors

Top view grids and 3D formats (Supplementary video) provide insight into group performance differences in position of force application. Junior and senior resident positive variability was higher than neurosurgeons and localized predominately to central tumor regions (Fig. 6). Despite no visual cues to help define borders, on receiving aspirator haptic feedback a second time from hard stiffness white tumors, residents increased force application. Neurosurgeons applied forces not dissimilar from those applied during the first tumor resection. This difference in psychomotor response may be related to neurosurgeons, who when faced with this situation, automatically apply their experience and knowledge concerning the possibility of damaging "normal" tissue and restrain force application.

Medium-Stiffness, Glioma-Like Tumors

Encountering a second medium-stiffness glioma-like tumor resulted in another variability pattern (Fig. 7). Junior residents had dispersed positive and negative variability, with the tumor interface in the right lower quadrant being a focus of negative variability (discussed in 3D formats). This suggests that junior residents obtaining haptic feedback for a second time from this particular tumor modulated force application at this interface, but extended this force application into the surrounding "normal" tissue. Senior residents had minimal positive variability and large regions of negative variability at and beyond this tumor interface. Our previous studies using force pyramids have also documented increased "normal" white matter injury in this model in junior and senior resident groups.[13] Neurosurgeon force and position application was very constant when faced with this tumor a second time.

Automaticity

One concern was that we had defined a consistency benchmark that no operator could achieve. In our study,

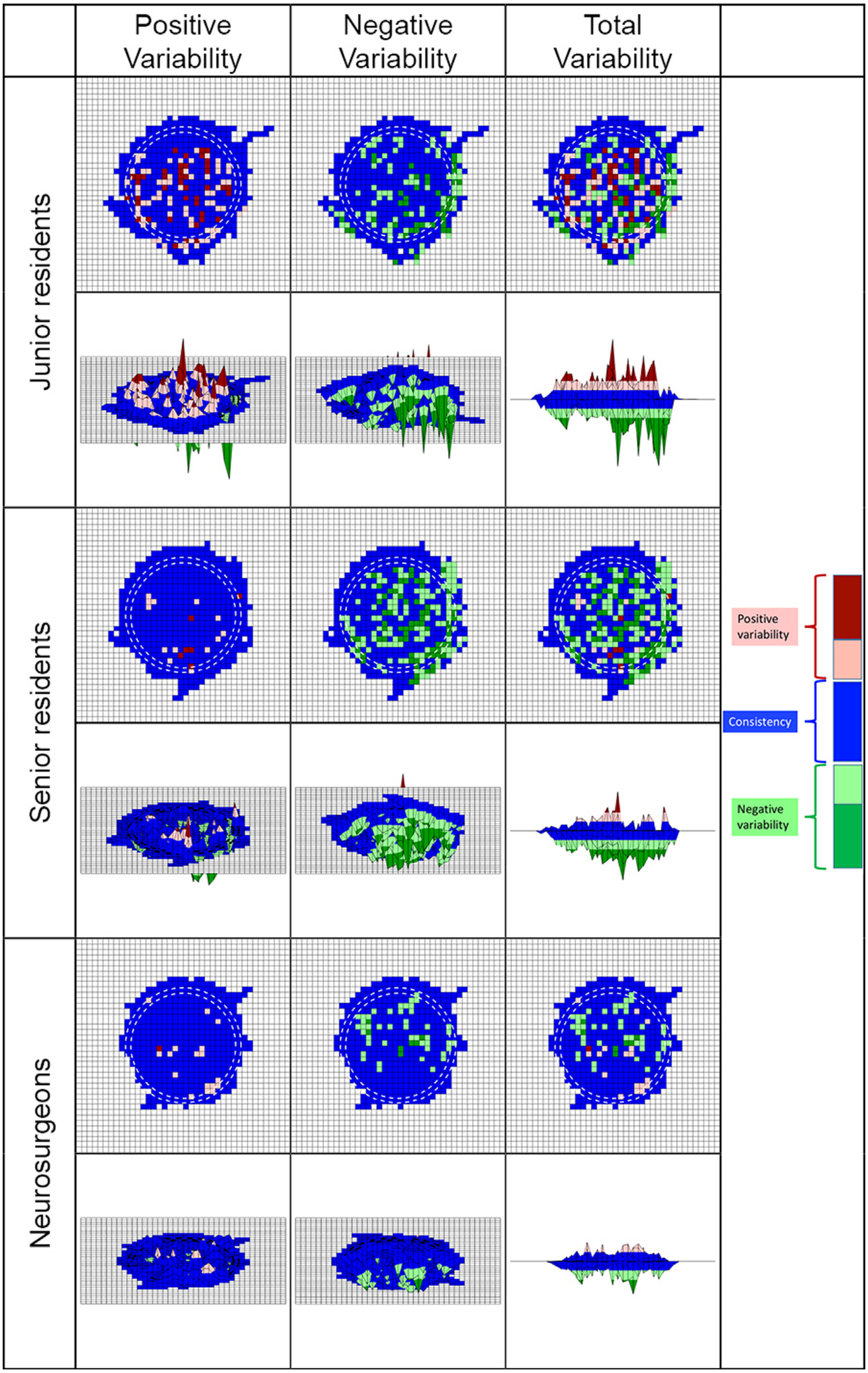

FIGURE 4. Percentage consistency and variability of force application for junior ($n = 8$) resident, senior ($n = 10$) resident, and neurosurgeon ($n = 9$) groups for (A) all tumors, (B) hard stiffness, white tumors, and (C) medium-stiffness, glioma-like tumors. Values represent means ± SEM, and lines indicate statistical significance $p < 0.05$.

4 participants (2 neurosurgeons, 1 senior resident, and 1 junior resident) demonstrated their ability in automaticity in some tumors reaching 100% consistency. This finding suggests that the consistency benchmark set in this study was attainable, but only a small number of individuals regularly performed at this level of automaticity.

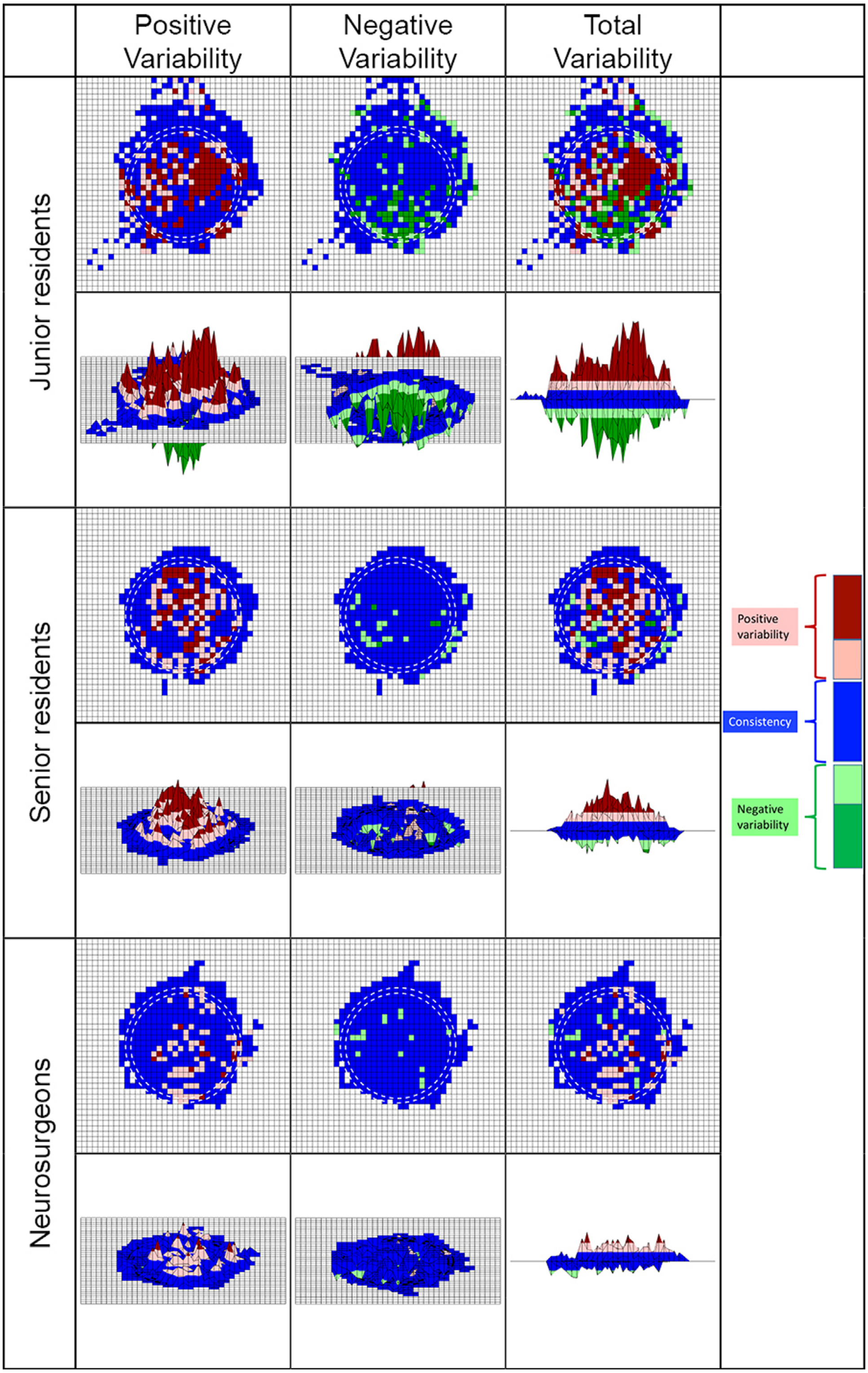

FIGURE 5. Percentage consistency, positive variability, and negative variability of force application for junior (*n* = 8) resident, senior (*n* = 10) resident, and neurosurgeon (*n* = 9) groups for (A) all tumors, (B) hard stiffness, white tumors, and (C) medium-stiffness, glioma-like tumors. Values represent means ± SEM, and lines indicate statistical significance $p < 0.05$.

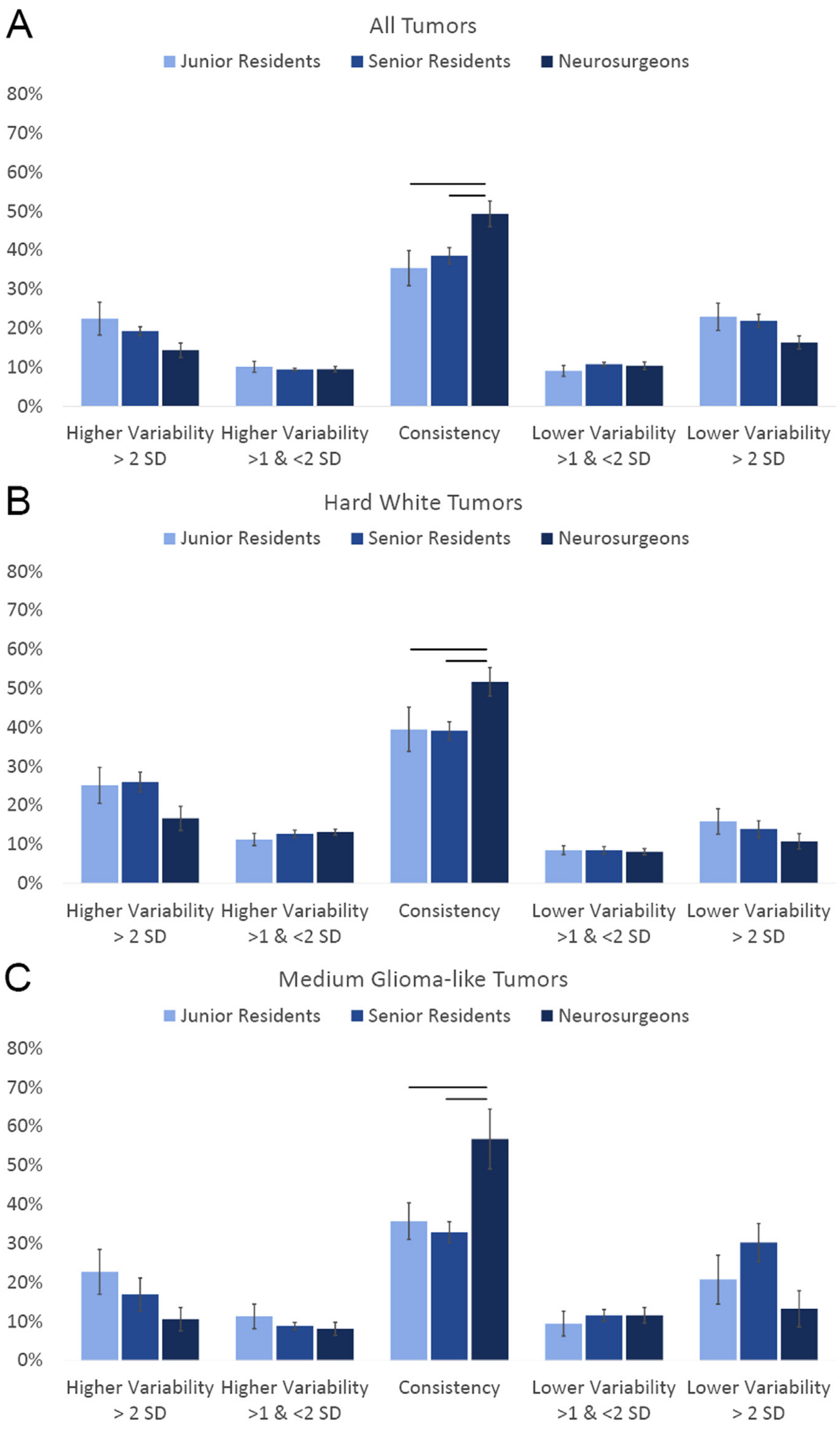

FIGURE 6. Top view grids and 3D formats of positive, negative, and total variability areas for hard stiffness, white tumors. Color bar outlines consistency, positive variability, and negative variability regions. Total, positive, and negative variability 3D formats all have a similar consistency area outlined to better assess differences. Color map outlines consistency (blue), positive variability (red), and negative variability (green) benchmarks.

DISCUSSION

This is the first study to address the question posed by the Fitts and Posner model, which predicted that "experts" (neurosurgeons) would be more autonomous than "novices" (residents) during their simulated neurosurgical operative resection when faced with similar tumors separated by other procedures. A second question was whether junior and

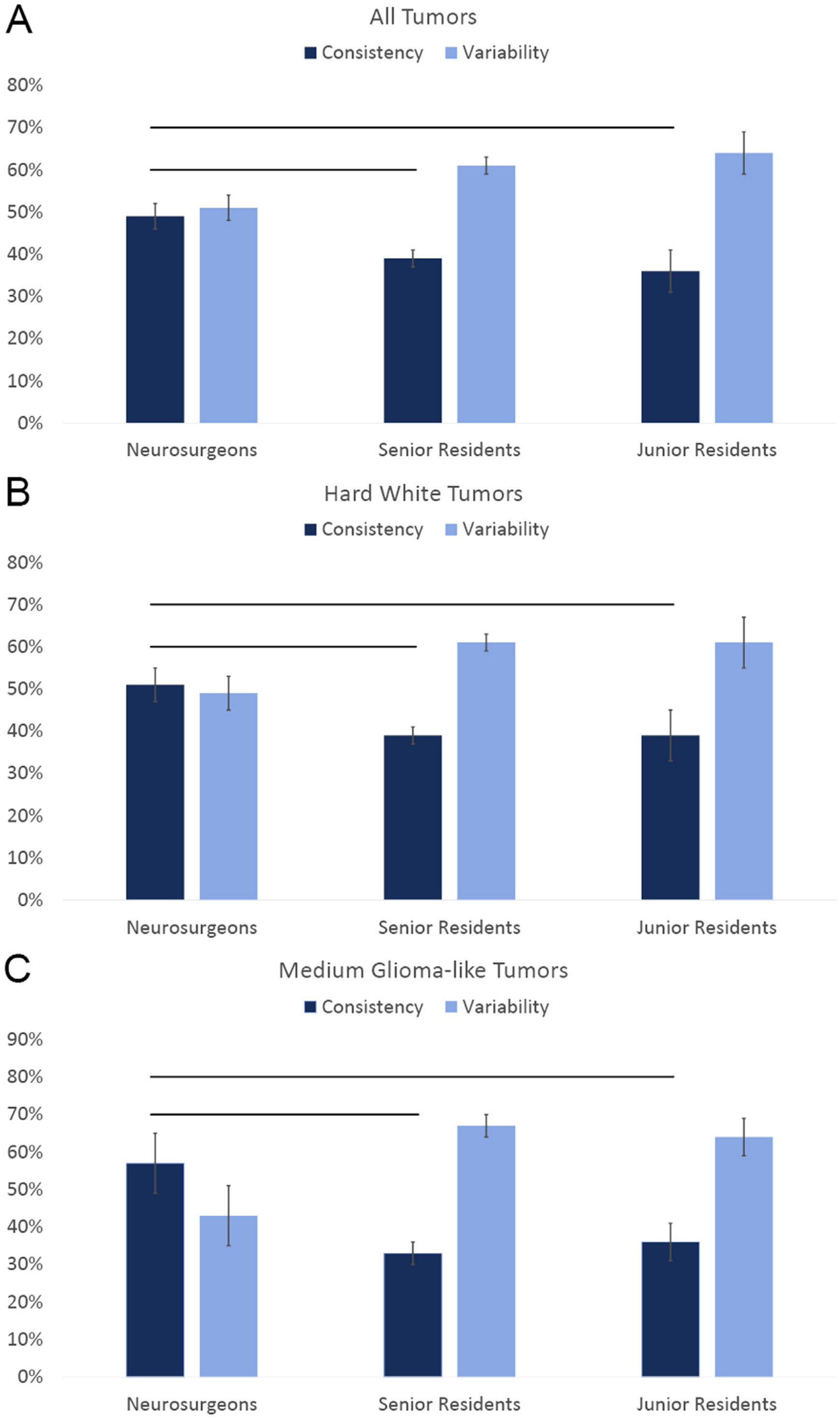

FIGURE 7. Top view grids and 3D formats of positive, negative, and total variability areas for medium-stiffness, glioma-like tumors. Color bar outlines consistency, positive variability, and negative variability regions. Total, positive, and negative variability 3D formats all have a similar consistency area outlined to better assess differences. Color outlines consistency (blue), positive variability (red), and negative variability (green) benchmarks.

senior residents would be in different phases of psychomotor learning. The high-fidelity NeuroVR simulator allowed development of a tumor resection model that mirrored neurosurgeon experience in neuro-oncology, that is, the neurosurgeons use comparable procedures when faced with similar tumors. The results that neurosurgeons are significantly more autonomous than resident groups support the Fitts and Posner model and are consistent with the concept that motor skill automaticity increases following residency completion. No significant progression of automaticity in the motor skills studied was identified when comparing resident groups. This supports the idea that both resident groups may be progressing through the associative phase of motor learning.

Neurosurgical Psychomotor Skills Script

Our results support placement of practicing neurosurgeons in the autonomous phase of motor performance. This concept implies that neurosurgeons, based on acquired experience, analyze specific tumor information without conscious awareness and automatically apply comparable forces in analogous tumor locations when faced with similar tumors. These findings support the presence of a "psychomotor skills script" that neurosurgeons develop and implement with increasing surgical knowledge.[31-33] Gioia and Poole defined script as "a schematic knowledge structure held in memory that specifies behavior or event sequences that are appropriate for specific situations" and script-processing as "the performance of the behaviors or events contained in the knowledge structure."[32] Another cognitive underpinning of medical education built on this script-based psychological theory is the "Illness script."[33,34] This describes how medical experts use a script-based clinical reasoning system that occurs automatically and unconsciously leading to efficient performance of diagnostic tasks.[34] The finding that "experts" (neurosurgeons) show a high degree of consistency of force and position application suggests the presence of a neurosurgical "psychomotor skills script." This concept is supported by functional Magnetic resonance imaging studies in musicians that link specific neural architecture to learning and performance and identify anatomical and functional neural connectivity regions predicting rates of new sensory-motor learning.[35] Our findings outline a "hidden skill" of neurosurgical psychomotor expertise: automaticity of force and position application.

Junior and Senior Residents Groups

No statistically significant difference in consistency between resident groups was identified suggesting that resident groups addressed in our study are not in different phases of the Fitts and Posner model. There are reasons for this result. First, this model proposes that in the cognitive stage the learner builds the component units of the task and in the associative stage the learner tries to link these units to perform the entire task. Both junior and senior residents may have assembled the basic cognitive components needed for completion of the simulation task required, and therefore are in the associative phase of motor skills learning. Support for this explanation is provided by studies by Ericsson[3] outlining a learning curve in which new skills are acquired at a fast initial rate followed by much slower rate of acquisition. Both resident groups could have completed the cognitive phase of fast rate of skills acquisition and may be in the slow rate of skills acquisition associative phase. Including medical students who had not acquired the intellectual components needed for task completion (cognitive phase) may have helped define the transition phase of the model. Second, in the Fitts and Posner model, each phase merges into the next with no sharp transition. If junior residents are merging into the associative phase while senior residents have not yet merged into an autonomous phase, it may be difficult to separate resident groups. Third, as the resident groups assessed displayed variable performance consistency, this may have made it difficult to identify specific skill sets based only on years of residency training. Our arbitrary cutoff between junior and senior residents is based only on time spent in residency training. Therefore, analyzing a skill only at a specific time point during residency training may not reflect the total experience and competency that particular resident has acquired. Another confounding factor was that 4 participants demonstrated excellent ability in automaticity for some tumors (100% consistency based on the benchmark we defined). This outlines that some individuals might have exceptional inherent automaticity of motor skills. In 2 previous studies using the NeuroVR platform, we identified participants with exceptional performance.[16,17] The Fitts and Posner model may not be appropriate when applied to individuals or groups possessing exceptional inherent motor skills. Reviewing data from these and other studies, we proposed a conceptual learning framework referred to as "Technical Abilities Customized Training." [17] A Technical Abilities Customized Training program would focus on accelerating the automaticity of top performers and improving areas of identified weakness.[17] Data from our studies can be used to develop proficiency automaticity performance benchmarks.[10] Using these benchmarks would allow both the identification of residents with exceptional automaticity skills and training paradigms to improve automaticity in surgical performance.

Strengths and Limitations of the Study

The importance of our results lies in the potential educational application in resident training. Psychomotor performance automaticity provides educators with another validated metric to monitor and improve trainee progress. Our group is assessing the role of automaticity in the safety, quality, efficiency, and cognitive interactive motor skills metrics we study.[7,11,13,30] The automaticity and force pyramid concepts may both be useful in defining the "surgical fingerprint" of neurosurgeons.[17]

The NeuroVR platform allowed testing of the Fitts and Posner model, but has limitations. First, our previous investigations demonstrated differences in psychomotor skills of left- and right-handed operators, so only right-handed participants were included.[17] Our results neither allow comment on automaticity ergonomics of left-handed operators nor allow comment on whether the automaticity definition that we have developed is the most appropriate.

Second, only a simulated aspirator was used in this investigation, not representative of instruments, and bimanual psychomotor skills employed during patient operations. Third, the different visual and haptic complexities, task duration, and spacing of tumors may not discriminate performance. Defining large populations of residents and neurosurgeons not experienced with virtual reality platforms is challenging. We enrolled 18 McGill residents and 1 McGill fellow that may limit applicability of our results. This study involved 9 neurosurgeons from 3 institutions with different areas of expertise, which is more representative of the general neurosurgical population. Although all tumor types showed higher consistency in the neurosurgeon group, this reached statistical significance in 2 of 9 tumors. It should be emphasized that our results do not show that consistency of force and position application is associated with improved operative performance or patient outcomes or both, and these questions need to be addressed.

CONCLUSION

Our results support the Fitts and Posner model of motor learning and are consistent with the concept that automaticity improves after completing residency training. Automaticity of force and position application is one motor skill relating to "expert" neurosurgical performance and may have potential educational application related to neurosurgical resident training.

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SUPPLEMENTARY MATERIAL

Supplementary data are available in the online version of this article at http://dx.doi.org/10.1016/j.jsurg.2017.06.018

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