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

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Abstract

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.

METHODS: Nine neurosurgeons, 10 senior residents and 8 junior residents resected 9 identical simulated tumors on two 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 utilized 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 utilized for the initial tumor.

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.

Résumé

OBJECTIF**:** Mettre à l'épreuve l'hypothèse que le modèle de Fitts et Posner en apprentissage de la motricité contribue à l'amélioration de l'habilité motrice autonome. Pour ce faire, nous avons évalué l'automaticité des neurochirurgiens et des résidents séniors et juniors, lors de chirurgies de deux tumeurs identiques qui se sont faites sous la plateforme de réalité virtuelle NeuroVR.

MÉTHODE: Pour reproduire un environnement semblable à la pratique actuelle en neurochirurgie, neuf tumeurs simulées identiques, de différente complexité visuelle et haptique, ont été reséquées à deux reprises. Il y a eu un total de 18 résections faites par neuf neurochirurgiens, 10 résidents séniors et 8 résidents juniors. La constance de la force appliquée a été utilisée comme point de mesure pour l'évaluation de l'automaticité. Celle-ci est définie par la quantité de force utilisée moins d'un écart-type au-dessus ou au-dessous de la force d'application moyenne. La quantité et l'endroit spécifique de l'application de force de la deuxième résection ont été comparés avec ceux de la première résection.

RÉSULTATS: Les neurochirurgiens ont manifesté une constance de force appliquée plus élevée, comparé au groupe de résidents. Des différences significatives ont été observées entre ces deux groupes de médecins lors des résections de tumeurs aux mêmes couleurs que le fond (blanches) de grande rigidité et celles de rigidité moyenne. Par contre, il n'y a pas de différence statistique de la constance de force d'application entre les deux groupes de résidents.

CONCLUSION: Sous la plateforme NeuroVR, les neurochirurgiens de niveau expert ont démontré un niveau avancé d'automaticité lors des chirurgies de tumeurs simulées identiques, séparées par une série de tumeurs différentes. Les résultats de cette étude valident le modèle d'apprentissage Fitts et Posner, tout en établissant que l'automaticité est améliorée suite à la fin de la formation des résidents.

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Preface and Contribution of Authors

This thesis was structured in a manuscript-based manner. The original manuscript has been submitted to the Journal of Neurosurgery on 2nd December 2016. The manuscript was edited by adding a more comprehensive introduction, methodology, results and discussion in line with the requirements of thesis submission by McGill University, Faculty of Graduate Studies.

The candidate functioned as the principle researcher for the study including data preparation, data analysis, data integration, results interpretation and writing of the scientific manuscript and submitting it.

Mr. Robin Sawaya MSc Candidate in the Integrated Program of Neuroscience in the Department of Neurology and Neurosurgery, McGill University was instrumental in the process of developing software (MATLAB) codes used for data analysis, figures assembly and critically reviewing the manuscript.

Mrs Duaa Olwi MSc, was instrumental in the process of statistical analysis and manuscript revision.

Dr. Gmaan Alzhrani MD MA, was essential in recruitment of participants of the study, helping to carry out the trial and manuscript revision.

Dr. Hamed Azarnoush PhD, shared his software (MATLAB) codes that helped in guiding the development of our new software (MATLAB) codes used in the data analysis.

Dr. Abdulrahman Jafar Sabbagh MBChB FRCSC, contributed in the discussions of the results and provided ideas which improved the study.

Dr. Ghusn Alsideiri MD, Dr. Khalid Bajunaid MD MSc, Dr. Fahad Alotaibi MD MSc, and Dr. Alexander Winkler-Schwartz MD contributed to the discussion of the results and reviewed the manuscript.

Dr. Rolando Del Maestro MD PhD, Director of the Neurosurgical Simulation Research and Training Center contributed to conception and design, data collection, results interpretation and critically reviewed the manuscript and my thesis.

Abbreviations

NRC = National Research Council of Canada

PGY = Postgraduate year

SD = Standard deviation

SEM= Standard Error of the Mean

3D = Three dimension

Introduction

Phases of Motor Skills Learning and Training in the Surgical Environment:

Based on W. L. Bryan and N. Harter (1899) observations on Morse Code learning along with other studies, Fitts and Posner (1967) proposed in their book "Human Performance" a model for phases of motor skill leaning. This model emphasized phases in which the learner passes when acquiring a new motor skill.(1) These phases were identified as the cognitive, associative and autonomous phases. In the cognitive phase the learner is trying to understand the task, the demands of the task and builds skill basic units and subroutines. Performance in that phase is slow, inconsistent with many errors. The associative phase is the intermediate phase where the learner is practicing the skill and modifying performance. Performance becomes faster with fewer errors. The autonomous phase is the final phase where the skill becomes autonomous. In that phase the skill becomes innate, fast, and consistent with few errors. The skill becomes less influenced by cognitive control and is performed with a lack of conscious awareness, less interfered by distractions and can be time-shared with other cognitive activities.(1-3) It is in the autonomous phase where the skill becomes secondary innate with parts of the skilled performance and judgment occurring intuitively.(4) For each individual phase of motor learning, Fitts and Posner (1967) proposed phase-specific needs that should be outlined to efficiently instruct a leaner and address his/her skill phase-specific needs. To advance the learner through the specific phase faster, expert instruction is necessary. An example of using this specific approach was shown on student pilots training where the average time to first solo was reduced from ten hours in the control group to three and a half hours in the experimental group.(1)

Neurosurgical training follows a traditional apprenticeship model as outlined by Lave (5) and Collin (6). This model is based on novice/expert interaction where a novice observes and assists an expert operating before he/she is permitted to acquire the skills necessary to operate.(7) The first defined apprenticeship model was formally implemented in the late nineteenth century by Dr. Halsted at Johns Hopkins Hospital. This model has dominated the North American and worldwide training of surgeons since it was proposed.(8, 9) In the apprenticeship model novices are trained without clear, explicit and specified technical skill goals and benchmarks nor with objectively tracked progress utilizing proficiency-based criteria that can aid in delivering level-specific training. Finally, trainees are evaluated subjectively as having attained surgical competence sufficient for independent practice.

Surgical competence has been defined as the ability to perform specific surgical skills successfully and encompasses knowledge, technical and social skills to solve familiar and novel situations to provide adequate patient care.(10, 11) This definition focuses on 'adequate' rather than expert or excellent patient care. What constitutes an expert in the field of surgery has not been clearly defined.(12) To provide excellent surgical patient care, the traditional apprenticeship model is in need of a re-evaluation. The report of The Institute of Medicine's "To Err is Human" has attributed surgical error to poor surgical training.(13) The duty-hour restriction protocols which have been implemented have led to decreased surgical exposure and training opportunities to practice and develop surgical skills.(14) In addition, research has contradicted the widely accepted concept that expertise is an inevitable consequence of many years of experience.(15) An essential element in the evaluation of psychomotor skills during neurosurgical training is the assessment of the specific skill necessary for expert performance. Proficiency-based training is practiced in many disciplines but neurosurgery technical skills leaning is linked to chronology, e.g., skills learned during specific periods of time in a residency program and in the operating room in a novice/expert apprenticeship model. Proficiency-based training and assessment implies that the trainee has achieved a set of validated pre-defined criteria to move to the next level in a controlled and safe learning environment. The development of objective learning benchmarks for technical expertise will be useful in the assessment and modification of trainee performance. The identification and validation of expert skills necessary to achieve expertise is therefore essential to develop the appropriate benchmarks for neurosurgical training.(12, 16)

Expert Performance Studies in other Domains and Expertise-Based Training:

Ericsson (2009) in his book "Development of Professional Expertise: Toward Measurement of Expert Performance and Design of Optimal Learning Environments" has provided a comprehensive overview of the sport, music and aviation literature on the acquisition and training of expert professional performance based on objective methods.(15) Sport expertise research has been implemented, becoming an essential part of athletic training.(4)

Expertise-based training is an instructional model introduced by Fadde (2009) to complement other established training models with the aim of decreasing the time required to develop novice into expert performance.(4) In the surgical technical skills domain, decreasing the time required for acquiring surgical technical skills has been demonstrated where junior-level learners reached skills level of intermediate-level residents with simulation training.(17) Therefore, decreasing the time for attaining expertise is possible. The core principles for developing an expertise-based training are: 1) Expert-novice research uncovers key skills that underlie expert performance, 2) Based on expert-novice research results and the uncovered skills, instructional activities could be designed to train novices. This type of instructional model has been utilized in sports by video-simulation training of baseball pitch recognition and psychomotor training of swing production.(4) Expert-novice research in the field of simulation in surgical and neurosurgical technical skills is increasing.(16, 18-27). However, the majority of this research has focused on face, content and construct validation of scenarios and/or assessment metrics. In neurosurgery, these assessed metrics have emphasized safety and efficiency of the brain tumor resection scenarios. These metrics are instrumental for validation of the specific scenarios in order to integrate them into a training curriculum. However, for exploring expert neurosurgical psychomotor performance, the utilization of the Fitts and Posner model allows us to assess skills such as automaticity of psychomotor performance. Automaticity is the ability to do things without occupying the mind with the required low level details; usually resulting from learning, repetition, and practice.

NeuroVR Simulator Platform:

The availability of NeuroVR simulator technology allows the testing of the role of automaticity in expert neurosurgical psychomotor performance. The National Research Council of Canada in collaboration with a group of neurosurgeons developed and evaluated the NeuroVR (formerly NeuroTouch) neurosurgical simulation platform. It is composed of a monitor that displays the virtual operative field along with virtual instruments that correspond to the physical instrument held in operator hands (Fig. 1A). The displayed image is in the form of 2 images side by side, which, with the help of the Stereoscope, are viewed as one (3D) image. The Stereoscope simulates the neurosurgical microscope used in the operating room to give a (3D) magnification of the operative field (Fig. 1B). Various physical instruments including: ultrasonic aspirator, suction, bipolar coagulator, microscissor and or drill can be connected to the NeuroVR platform depending on the operative scenario needed. These instruments have similar physical size, shape, function and tactile feel as those used in real surgery. Each instrument is connected to the NeuroTouch platform through a haptic micromanipulator device that tracks the movement of the instrument and delivers the feeling of the tissue (haptics) to the interacting participant based on the programmed mechanical properties (Fig. 1C).(28-30)

Objective of the Study

The objective of the study is to assess the automaticity of neurosurgeons, and senior and junior residents when operating on 2 identical tumors using the NeuroVR virtual reality simulation platform.

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

The preceding work was augmented with additional material and discussion to reflect the requirement of thesis for Master of Science in Experimental Surgery

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Introduction

The complex term ‘expertise’ has no exact definition as related to neurosurgical psychomotor performance, however, achieving expertise in neurosurgery technical skills is an aspiration goal.(12, 24) 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 model consisting of three progressive phases of motor skills learning dependent on deliberate practice through which a learner passes when acquiring new skills: cognitive, associative and autonomous.(1) In the cognitive phase, the learner builds the component units of the skill and consciously performs the task slowly, with numerous errors and marked inconsistency. The performance becomes faster, more accurate and consistent in the associative phase. In the final autonomous phase the skill becomes habitual, executed unconsciously with extreme fluency, accuracy and consistency of performance.(1-3) If this model pertains to the neurosurgical acquisition of operative skills, a number components of this model should be both testable and true. During training, students should progress through the three phases outlined. Our group has developed and validated a series of psychomotor metrics that objectively measure manual performance in medical students, residents and neurosurgeons during the resection of virtual reality tumors utilizing the NeuroVR platform.(16, 18, 19, 22, 24, 25, 28, 29, 31-33) These results are consistent with the model involving fluency and accuracy of manual psychomotor performance during the resection of simulated tumors.(22, 31, 32) ‘Experts’ in the autonomous stage of learning faced with similar operative pathologies should demonstrate significantly more consistency in their surgical approach. Consistency in performance is the feature that most distinguishes experts from novices.(34) The importance and the positive impact of consistency in sports performance is well established.(34-39) Neurosurgeons involved in surgical oncology are faced with a wide variety of tumor pathologies involving multiple surgical approaches. However, similar tumors do present at different times requiring comparable neurosurgical procedures.

One testable question posed by the Fitts and Posner model would be: Are 'experts' more autonomous in their operative resection when faced with identical tumors on different occasions separated by other 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 identical tumors by the neurosurgeon and resident groups.

Methods

Subjects

Nine board certified and practicing neurosurgeons from 3 institutions, 10 senior (9 PGY 4-6 and 1 fellow PGY-7) and 8 junior residents (PGY 1 – 3) from McGill University participated in the study. The fellow included had just completed neurosurgical residency and started a fellowship. It was considered appropriate to place the fellow in the resident group since adding or excluding this individual did not change statistical results. No participant had had previous experience with the NeuroVR simulator. All participants signed a consent approved by McGill University Health Centre Research Board before entering the study. Since we have documented significant differences in psychomotor performance based on the ergonomics of handedness only dominant right-handed participants were assessed in this study.(31)

NeuroVR Simulator

The previously described NeuroVR (formerly NeuroTouch) platform was used to conduct the study.(16, 18-25, 28-33, 40) Tumor resection was performed using a simulated ultrasonic aspirator held in the right hand (Fig. 2A).

Simulation Scenarios

To address the study question, a scenario was utilized that we had previously studied which involved resection of 9 identical simulated brain tumors on 2 separate occasions (total of 18 procedures) separated by removal of tumors with different complexities (Fig. 2B).(16, 18, 25, 31) To prevent the operator from predicting when the next identical tumor would appear in the resection sequence, the 2 identical ellipsoidal tumors were separated by between 4 and 12 different tumors (Fig. 1B, C, D). Each of the 6 scenarios utilized had 3 tumors of varying complexities involving color (black, glioma-like and white which is similar to background) and Young's modulus stiffness (3 kPa, soft, 9 kPa, medium and 15 kPa, hard) to maximize differences between tumors. A white background with soft tumor stiffness, 3 kPa represented the surrounding 'normal' white matter (Fig. 2C). Three minutes were allowed for removal of each of the 18 tumors one at a time in a predefined order (Fig. 2B) with a 1-minute mandatory rest time between each tumor resection. Each operator was given a practice scenario to become familiar with the procedure but data from this tumor resection was not used in analysis. Participants did not know the purpose of the study or the metrics used to assess performance. Each participant was specifically instructed in verbal and written instructions that the goal of the simulation was to remove each tumor with minimal removal of the background tissue using a simulated aspirator.

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. For this study automaticity for tumor resection was defined as: force application in Newtons (N) within a distinct consistency benchmark when resecting two 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 in our automaticity studies by using each group's mean for all tumors and each individual tumor as each group's baseline. Since 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 (Fig. 3 and 4). A number of other consistency benchmarks were also explored and the results were not different from those employed in this study. Total variability in performance was therefore considered to occur when forces were applied above or below the consistency benchmark range (Fig. 3 and 4). Positive variability was defined as force application above and negative variability was defined as force application below this consistency benchmark range (Fig. 3 and 4). Total variability can be considered the sum of both positive and negative variability.

Analysis of Force Application

For each tumor, the total application of forces at the same location (xy-location) was averaged. To compare the two identical tumors for consistency of force application, the average forces applied at each xy-location during first identical tumor resection (Fig. 3A) were subtracted from the average forces applied at the comparable xy-location during the second identical tumor resection (Fig. 3B) and the differences were quantitated (Fig. 3C). Spatial representations of force difference were created and represented by 3D formats (Fig. 3D) and top view grids (Fig. 3E). These spatial representations were colored to represent locations of consistency and variability in performance. Psychomotor performance consistency is calculated as the area of each group's mean ± 0.018 N and are outlined in blue (Fig. 3D and E). Psychomotor performance variability is calculated as all areas > than 0.018 N above or below the mean value for that group and outlined in shades of red and green (Fig. 3D and E). Red colors indicate spatial areas of positive variability where the participant applied forces > 0.018 N 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 N and > 0.036 N and > 0.036 N lower in the second compared to the first tumor (Fig. 3).

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 identical 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 N and > 0.036 N) and negative (<0.018 to <0.036 N 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 analyses were performed using STATA version 14.0 (Stata Corp, College Station, Texas, USA). Continuous and categorical variables were described using means and percentages respectively. For comparison of consistency among the three groups, Kruskal-Wallis test was used followed by Dunn's post-hoc test for pairwise comparisons. Values are represented as means ± SEM and p values < 0.05 were considered significant.

Results

Demographics

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

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

Figure 4 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 sections of the tumor.

Consistency of Performance

Consistency of force application was utilized as one metric to assess automaticity. When total consistency for all tumors was assessed the neurosurgeon group showed a statistically significant higher consistency in performance than resident groups (Fig. 5A). There was no statistically significant difference between resident groups (Fig. 5A). 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. 5B 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 6A 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. 6A). 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. 6B 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 provide insight into group performance differences in position of force application. Total variability 3D formats provide a visual representation of the progressive changes in force application. Junior and senior resident positive variability was higher than neurosurgeons and localized predominately to central tumor regions (Fig. 7). 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 obtaining similar feedback applied forces not dissimilar from those applied during the first tumor resection. This difference in psychomotor response may be related to neurosurgeons 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

When encountering a second medium stiffness glioma-like tumor a different pattern of variability was seen (Fig. 8). Junior residents had dispersed positive and negative variability with the tumor-interface in the right lower quadrant being a focus of negative variability as documented in the 3D formats. This suggests that junior residents obtaining haptic feedback for a second time from this tumor modulated force application at this interface but extended this force application into the surrounding 'normal' white matter. 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.(32) Neurosurgeon force and position application was very constant when faced with this tumor a second time.

Automaticity

Since consistency of force application was a metric utilized to assess automaticity, one concern was that we defined a consistency benchmark that no operator could achieve. In our study, 4 participants (1 junior, 1 senior resident and 2 neurosurgeons) demonstrated automaticity ability 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.

Discussion

Are Neurosurgeons More Autonomous than Senior and Junior Residents?

The question addressed in this study was the Fitts and Posner model which predicted that 'experts' (neurosurgeons) would be more autonomous than 'novices' (residents) in their operative resection when faced with similar tumors separated by other procedures. A second question linked to this model was whether junior and senior residents would be in different phases of psychomotor learning. The high-fidelity NeuroVR simulator allowed development of a tumor resection model which mirrored neurosurgeon experience in neuro-oncology. Namely that neurosurgeons utilize comparable procedures when faced with similar tumors. The results that neurosurgeons are significantly more autonomous than resident groups support the Fitts and Posner model. This finding is consistent with the concept that motor skill automaticity increases following completion of residency. No significant progression of automaticity in the motor skills we studied was found when resident groups were compared. This supports the idea that both groups may be progressing through the associative phase of motor learning.

Neurosurgical Psychomotor Skills Script

Our results are supportive of placement of practicing neurosurgeons in an autonomous phase of motor performance. This concept implies that neurosurgeons based on their experience analyze specific tumor information without conscious awareness and automatically apply comparable forces in analogous tumor locations when faced with similar tumors. This implies the presence of a psychomotor skills script that neurosurgeons develop and implement with increasing surgical knowledge. The concept of "script" is a well-studied psychological theory.(41, 42) It was first introduced by Silvan Tomkins (1954).(43) It has since been modified and extended in various domains of psychology: cognitive, social, learning, developmental and clinical.(41) 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".(42) Another cognitive underpinning of medical education built on this script-based psychological theory is the "Illness script" proposed by Custers, Henny and Schmidt (1996).(44-46) This describes how medical experts use a script-based clinical reasoning system which occurs automatically and unconsciously leading to an efficient performance of diagnostic tasks.(44) The finding that 'experts' (neurosurgeons) show a high degree of consistency of position and force application when resecting similar tumors suggests the presence of a neurosurgical motor script. This concept is supported by functional MRI studies in musicians that link specific neural architecture to learning and performance and identify anatomical and functional neural connectivity regions predictive of rate of new sensory-motor learning.(47, 48) Our findings outline a 'hidden skill' of neurosurgical psychomotor expertise, automaticity of position and force application. Further studies are in progress to define other components of the neurosurgical psychomotor skills script.

Junior and Senior Resident Groups

No statistical 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 number of reasons for this result. First, this model proposes that in the cognitive stage the leaner builds the component units of the task and in the associative stage he/she tries to link these units to perform the whole 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 outlining a learning curve in which new skills are acquired at a fast initial rate followed by much slower rate of acquisition.(49) 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 resident have not yet merged into an autonomous phase it may be difficult to separate resident groups. Third, since the resident groups assessed displayed variations in performance consistency, this may have made it difficult to identify specific skill sets based only on years of residency training. The cutoff between junior and senior residents is arbitrary and only based on time spent in residency training. Therefore, when analyzing a skill only at a specific time during residency training may not reflect the total experience that particular resident has acquired. Fourth, having a larger number of residents in which the technical skills could be assessed during each year of residency training might have provided more accurate differentiation of skills. Another confounding factor was that

4 participants demonstrated excellent automaticity ability for some tumors (100% consistency based on the benchmark we defined). This finding highlights that some individuals might have exceptional inherent automaticity of motor skills. In two previous studies utilizing the NeuroTouch/NeuroVR platform we identified participants with exceptional performance.(19, 20) After reviewing the data from these and other studies we proposed a conceptual learning framework referred to as "Technical Abilities Customized Training" (TACT). A program in neurosurgical TACT would focus on both accelerating top performers automaticity and improving areas of identified weakness.(33) The Fitts and Posner model of motor learning may not be useful when applied to individuals and/or groups possessing exceptional inherent motor skills.

Fitts and Posner Model of Phases of Skill Learning and Other Models of Motor Learning

The Fitts and Posner model was chosen as the model of reference in our study. There is another schemata of discrete motor skill learning proposed by Schmidt (1975). This schema aims to explain the information that the individual stores when he/she learns a new motor skill. It involves 4 levels of information; the initial condition, where visual, auditory and proprioceptive information are used to recognize the state of the muscular system and the surrounding environment prior to plan the motor response. The response specifications; involving specification of the movement pattern for example, speed and amount of force. The sensory consequences; the sensory feed-back received after the movement is attempted. Finally, the response outcome; whether the response was successful as originally planned or not.(50) The schemata proposed by Schmidt is mainly concerned with the cognitive aspect of motor leaning as it describes how a movement is planned and stored.

The Fitts and Posner model was chosen because it has a discrete motor component that starts from describing novices (cognitive phase) till experts (autonomous phase) with specific descriptions of each phase characteristics which makes it amenable to be tested using NeuroVR.

Strengths and Limitations of the Study

The importance of our results lies in their potential educational application in neurosurgical resident training. Automaticity defined as consistency of position and force application when operating on similar tumors is a characteristic of 'expert' psychomotor skill performance. Psychomotor performance automaticity provides educators with another validated metric to both monitor and improve trainee progress. The development of automaticity performance benchmarks and incorporation of this metric into neurosurgical training curriculum is being studied.(18, 25) Our group is also assessing the role of automaticity in the safety, quality, efficiency and cognitive interactive motor skills metrics that we study.(22-24) The automaticity concept, like that of the force pyramid, may also be useful in further defining the 'surgical fingerprint' of individual neurosurgeons.(31)

The NeuroVR platform has allowed testing of the Fitts and Posner model but one should be mindful of the limitations of these technologies. First, since our previous investigations had demonstrated marked differences in the psychomotor skills of left and right handed operators only right-handed participants were included in this study.(31) Our results do not allow comment on automaticity ergonomics of left-handed operators nor whether the automaticity definition that we have developed is the most appropriate to assess neurosurgical automaticity. Since we focused our research on the consistency component of automaticity, our studies do not allow us to comment on the speed and/or accuracy elements of automaticity. Additionally, it should be emphasized that consistency of performance can encompass a wide range of metrics including but not limited to consistency of force application, consistency in rate of tumor resection and amount of normal brain injury. Since excessive force application is felt to be related to surrounding normal tissue damage and is a safety metric, our ongoing studies involve further outlining this relationship. It was therefore considered important as a preliminary step to analyze the automaticity of force application among neurosurgeons (experts) and residents (novice) groups.(22) To further our knowledge on the role of automaticity in neurosurgical expertise, studies involving more complex tumors adjacent to the motor cortex and involving bleeding are presently being studied. Second, since only a simulated aspirator was utilized in this investigation this is not representative of the instruments and bimanual psychomotor skills employed during patient tumor resections. Third, the different visual and haptic complexities, task duration and spacing of identical simulated tumors may not discriminate operator performance. More realistic complex tumor scenarios involving use of bimanual instruments to control simulated bleeding are being studied. Defining large populations of residents and neurosurgeons not experienced with virtual reality platforms is challenging. We were able to identify and enroll 18 McGill residents and 1 McGill fellow which may limit applicability of our results. This study involved 9 neurosurgeons from 3 institutions with different areas of expertise which we feel 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. The authors believe that increasing study participants would result in further tumor types being added to this group. It should be emphasized that our results do not show that consistency of position and force application is associated with improved performance and/or patient outcomes.

Overall Conclusions and Future Directions

Conclusions

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 position and force application is one motor skill relating to 'expert' neurosurgical performance and deserves further study to outline its role in neurosurgical education.

Future Directions

In light of our study finding, we will be testing the concept of consistency of force application when operating a complex tumor with irregular shape and greater depth. Additionally, we will be testing the concept of consistency in force application including left handed participants. We propose studying the concept of consistency of performance in terms of amount of tumor resected and collateral normal brain damage along with other possible hidden experts' neurosurgical operative skills.

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Figures

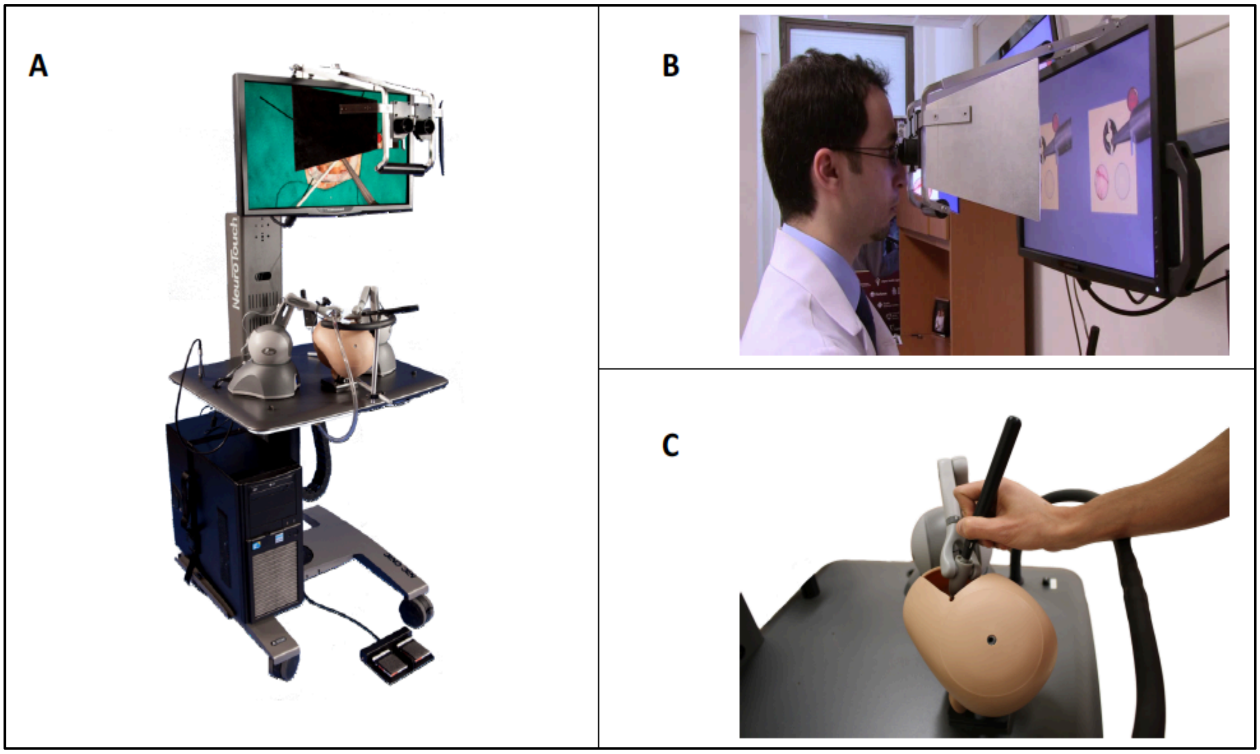


Figure 1. A: The NeuroVR Simulation Platform. B: A participant performing the resection scenarios. Simulated operative field is viewed through the stereoscope. C: A participant holding the simulated ultrasonic aspirator. The ultrasonic aspirator is connected to the haptic micromanipulator device.

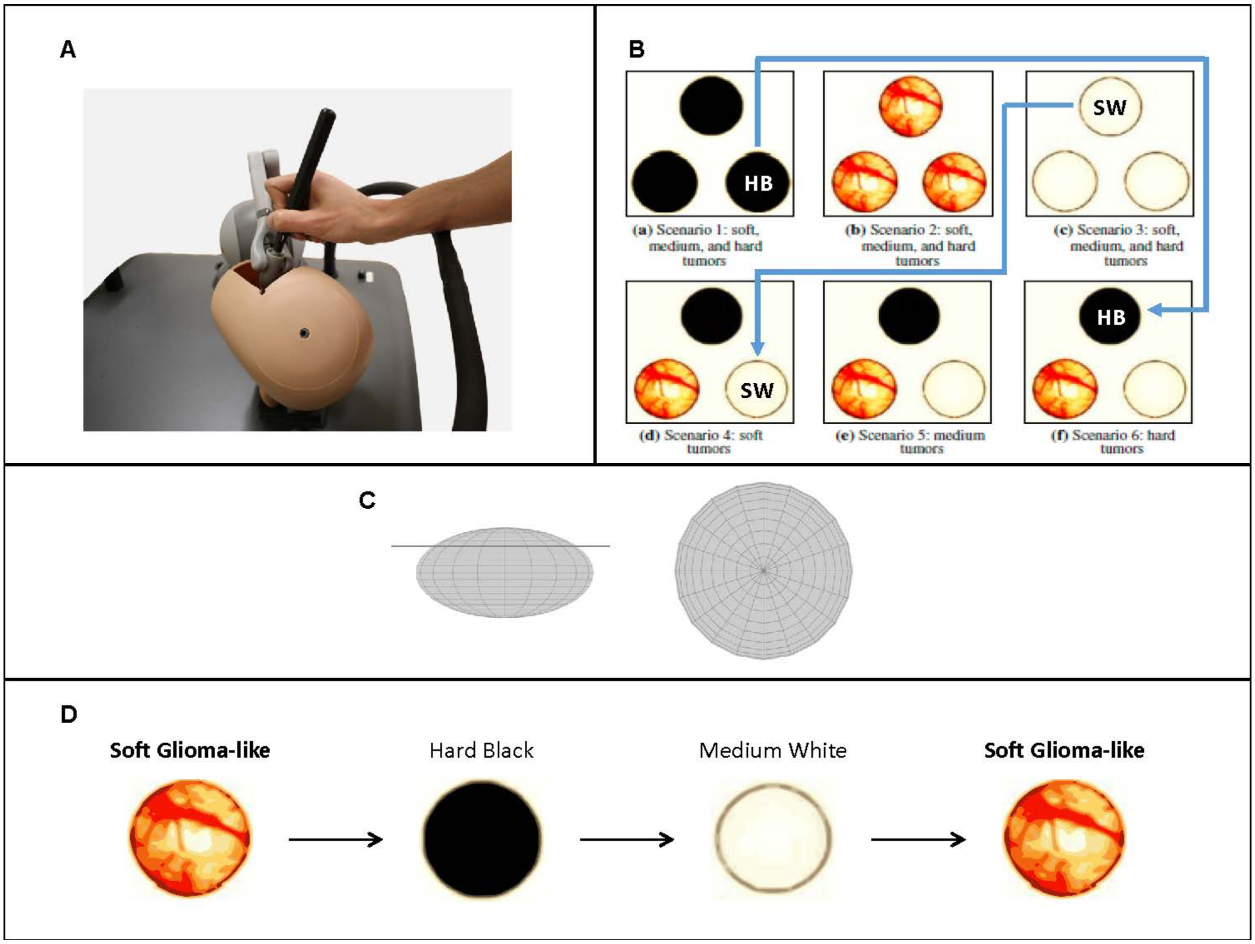


Figure 2. A: Operator with simulated aspirator in right hand.

B: The six 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 two 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.

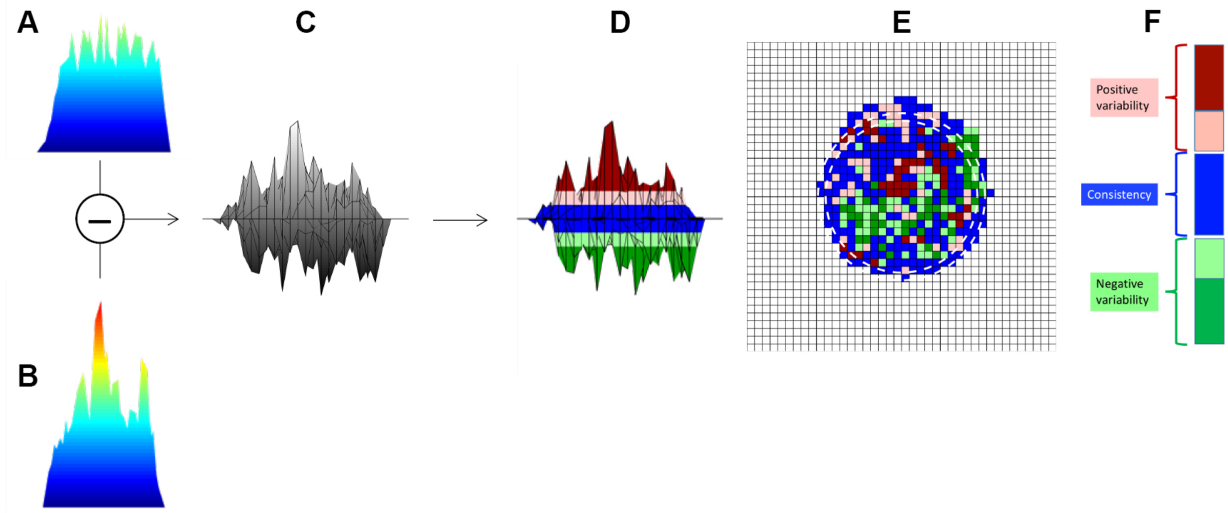


Figure 3. Generation of 3D formats and top view grids. A: Force pyramid of first resected tumor. B: Force pyramid of second resected tumor. C: Result of subtraction of force pyramid A from force pyramid B. D: Color assignment of results based on consistency positive and negative variability benchmarks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

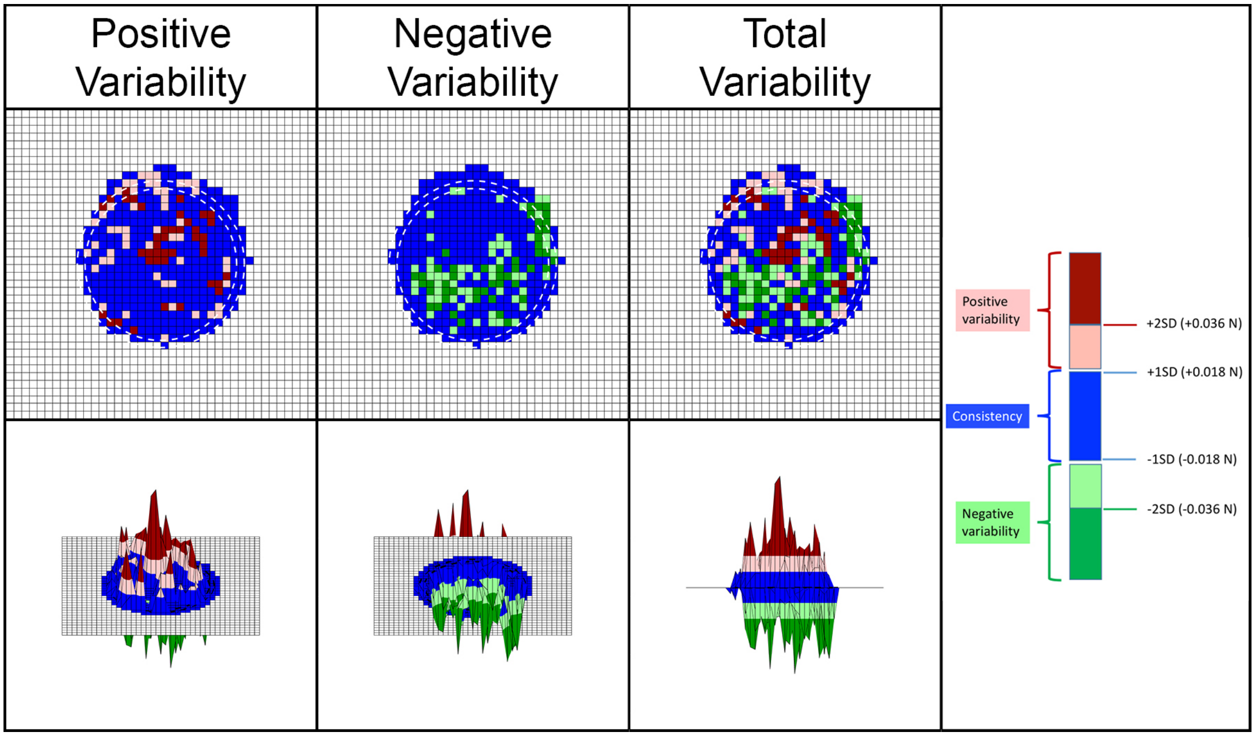


Figure 4. Examples of top view grids and 3D formats of positive, negative and total variability for a participant resecting a soft glioma-like tumor. Color map outlines consistency (blue), positive (red) and negative (green) variability benchmarks.

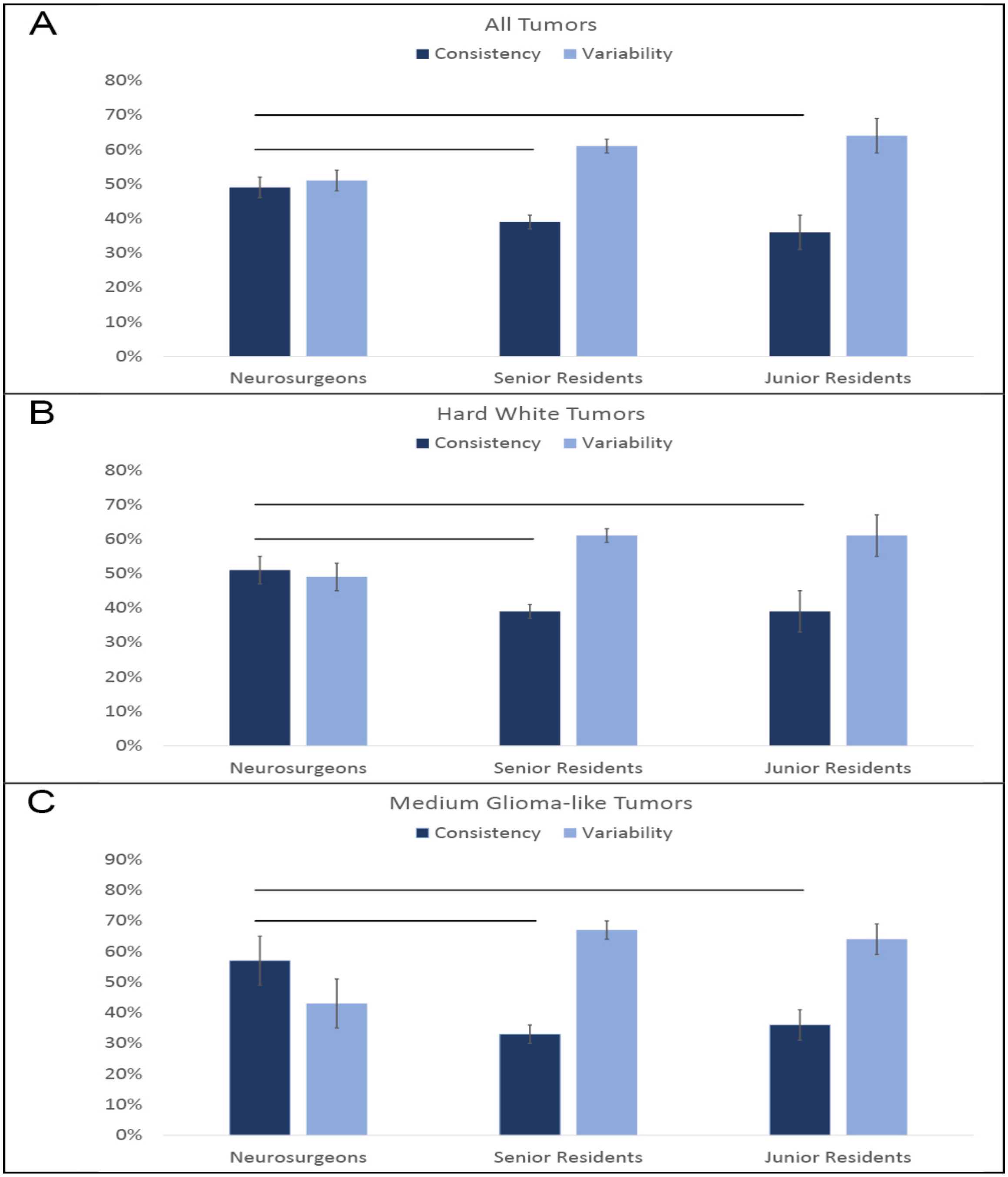


Figure 5. A: Percentage consistency and variability of force application for neurosurgeon (n=9), senior (n=10) and junior (n=8) resident groups for A: All tumors. B: Hard stiffness, white tumors and C: Medium stiffness, glioma-like tumors. Values represent means ± SEM and lines indicate statistical significance $p < 0.05$.

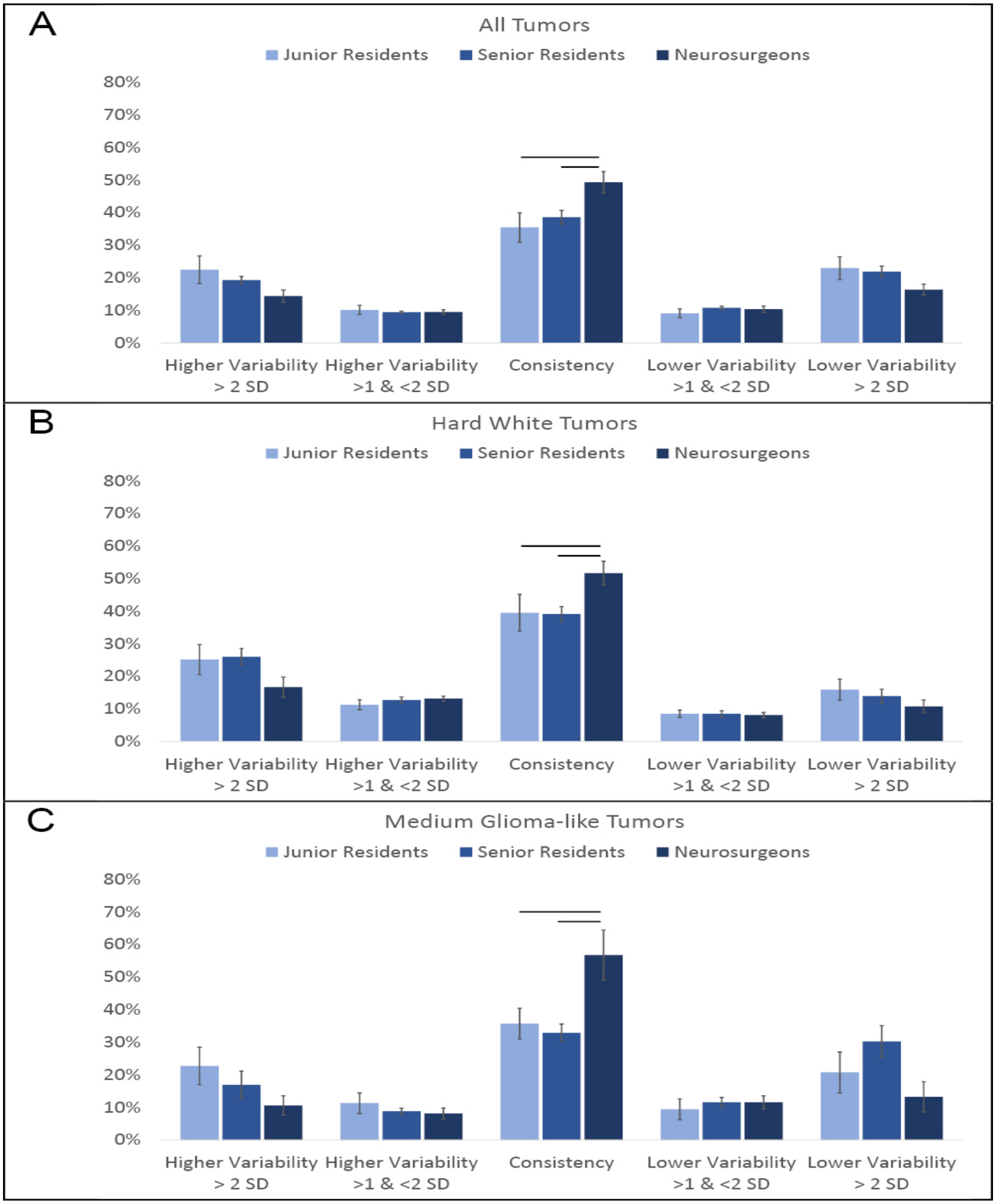


Figure 6. Percentage consistency, positive and negative variability of force application of neurosurgeon (n=9), senior (n=10) and junior (n=8) resident groups for A: All tumors. B: Hard stiffness, white tumors and C: Medium stiffness, Glioma-like tumors. Values represent means ± SEM and lines indicate statistical significance $p < 0.05$.

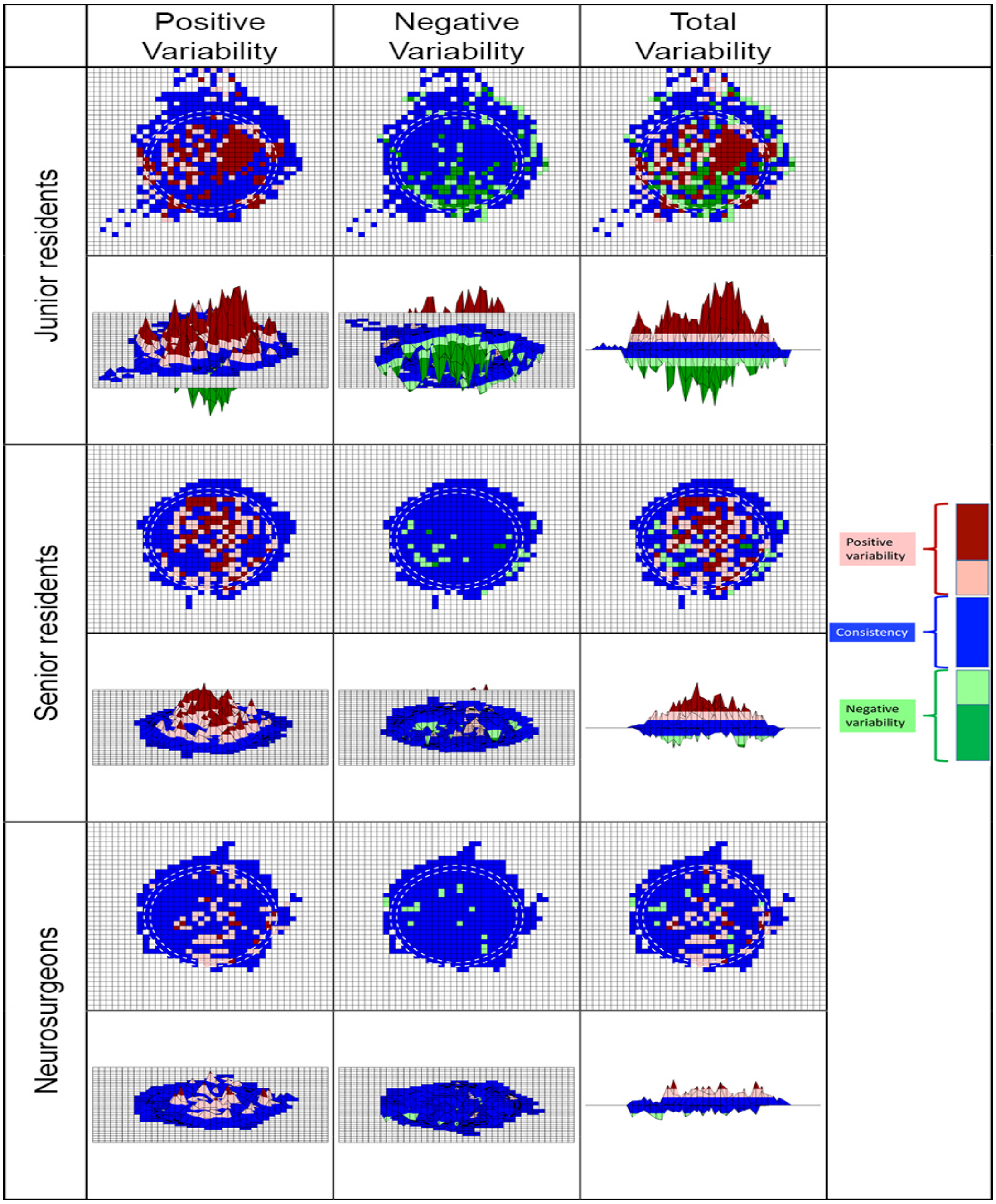


Figure 7. Top view grids and 3D formats of positive, negative and total variability areas for hard stiffness, white tumors. Color bar outlines consistency, positive and negative variability regions. Total, positive and negative variability 3D formats all have a similar consistency area outlined to better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

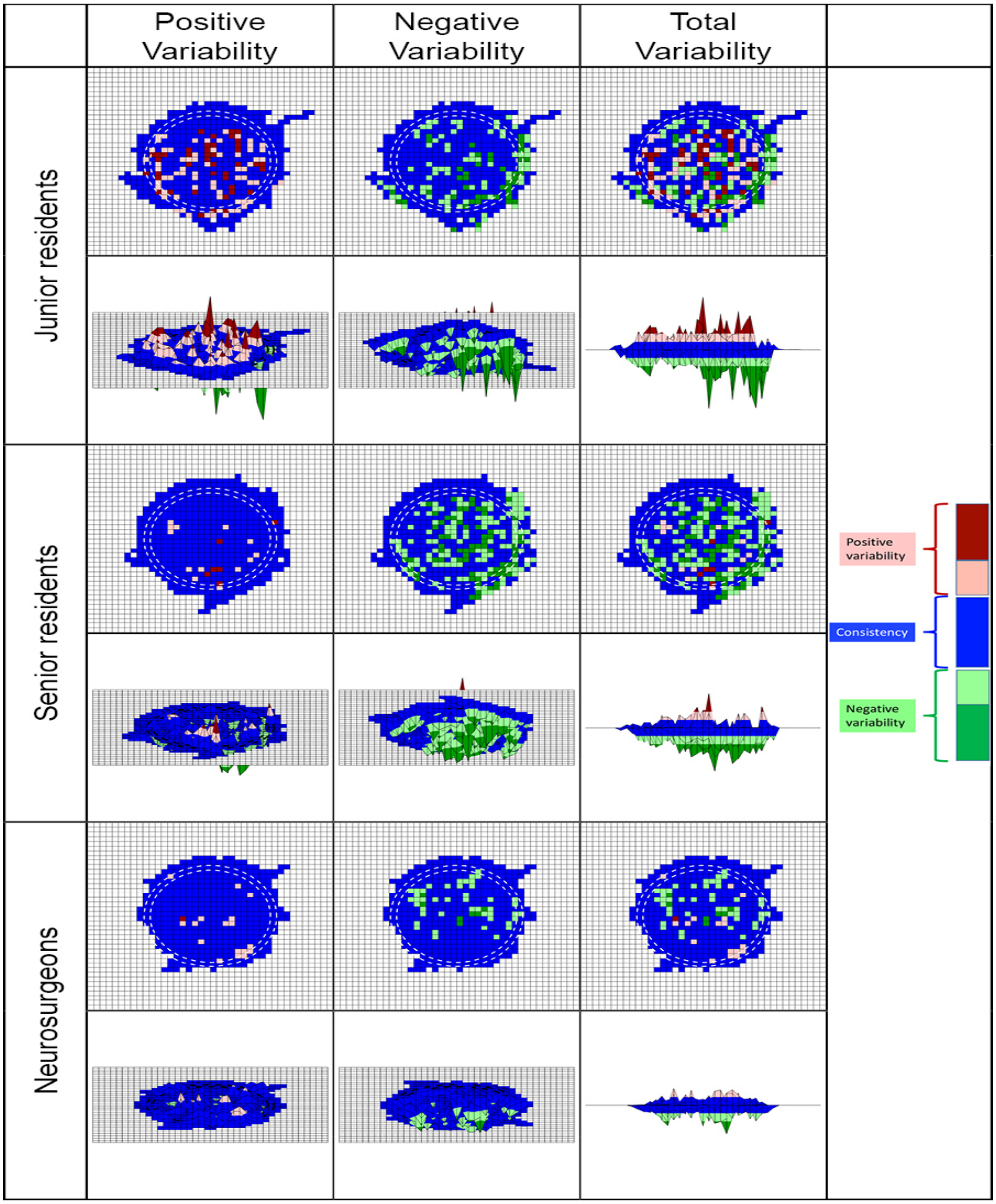


Figure 8. Top view grids and 3D formats of positive, negative and total variability areas for medium stiffness, glioma-like tumors. Color bar outlines consistency, positive and negative variability regions. Total, positive and negative variability 3D formats all have a similar consistency area outlined to better assess differences. Color outlines consistency (blue), positive (red) and negative (green) variability benchmarks.

Appendices

Appendix A

INFORMED CONSENT FORM

Study: *Neurosurgical virtual reality simulator validation*

Principal Investigator: Rolando Del Maestro

Study Site: Montreal Neurological Hospital
3801 University Street
Montreal, Qc, H3A 2B4

We are asking if you would be willing to participate in a research study. This document describes the rationale, nature, and your potential role in the study. Please read it carefully. Should you decide to participate, please identify and have answered any questions that you may have prior to signing the attached consent form.

Purpose of the Research

The main objective of this study is to develop a valid virtual reality neurosurgical simulator. This simulator will eventually be used in the training and evaluation of neurosurgical residents and staff performances. Currently, there is no virtual reality neurosurgical simulator available commercially. This project represents a first step in the development of such a simulator. The objectives of this study are to develop valid metrics (measurements) of performance as well as improving both the simulator itself and what it measures. If you were a participant in a previous study called *Global Assessment Tool for the Evaluation of Intraoperative Neurosurgical Skills,* you will be asked to allow the data from this previous study to be used to analyze the similarity of your performance in the operating room and on the simulator.

Description of Research Methodology

Participants will be recruited to participate in the development of the neurosurgical simulator. A participant from the MNH can be any staff, resident or medical student who has the possibility of using the simulator. Also, anybody who can have access to the simulator is a potential participant (engineer, gamer, etc.) Subjects will be asked for their consent to participate in the study by allowing recordings of the data produced while using the simulator. These data include the metrics of the performance (measurement), the virtual video recording of the virtual surgery and the various feedbacks the participants will provide to improve the simulator. The virtual videos will then be assessed by two blinded raters. These evaluators will assess the technical skills of the surgeon performing the surgical manipulations on the videos according to the tool developed by the researchers. This tool is a 5-point Likert scale based on the Global Rating Scale introduced by Reznick et al. for open surgery. It is modified to include items that capture important technical skills in neurosurgery. The evaluations will be done blindly, i.e. the evaluator will not have a priori knowledge of the level of experience of the surgeon to be evaluated. The identity and training level of the surgeon (including both resident and staff) are masked from the evaluators. For the participants where data from the *Global Assessment Tool for the Evaluation of Intraoperative Neurosurgical Skills* study are available, a comparison between their performance in the operating room and on the simulator will be done with the permission of the participant.

Potential Benefits

Any participants in this study can benefit by having access to practice material in the field of neurosurgery. This could theoretically improve their performance and technical skills, although no formal studies have shown that point with this particular simulator.

As a participant, you can be provided with some useful feedback upon assessment of your skills. This may help you identify areas of weakness that may require further practice or training. Although this assessment will have no implication on your formal academic skills assessment, it may aid you in improving areas of weakness prior to such evaluations. The feedback will be given to you by one of the researcher as well as by simulator itself through messages on the screen. If you are currently a trainee in neurosurgery, we will ensure that your performance will not be reported to your academic supervisor and will not have any effect on your academic record.

Potential Harms, Injuries, Discomforts or Inconvenience

A potential risk is that you may be identified by the study evaluators. Careful measures will be taken to blind the evaluators to prevent this from occurring, but on the chance that it should occur, we assure you that your technical performance will have no bearing on your academic evaluations or on your professional relationships with the study evaluators/investigators. As well, your willingness/unwillingness to participate in the study will have no bearing on academic evaluations or professional relationships.

Confidentiality

We request your signed consent for participating in the study. Your name is required in order to keep track of your level of training, handedness and your anonymous code/subject number on a separate "*Participant Data Collection Form*". For data analysis purposes you will be assigned a code number known only to the principal investigator and all data collected will be identified using only this code. Again, care will be taken to mask your identity and level of training by using virtual videos bearing no identifying data. Identifying information will be kept in a locked file in the Division of Neurosurgery offices at the Montreal Neurological Hospital. Confidentiality will be respected and no information that discloses your identity will be released or published without your consent. The study data will be kept until full analyses have been performed and research has been published. All electronic files will be erased and hard copies will be shredded no longer than seven years after the completion of the study.

A Research Ethics Board or Quality Assurance Officers duly authorized by it may access study data for audit purposes.

Participation

Your participation is voluntary. You are free to withdraw from this study at any point without any penalty. Upon withdrawal, your data would be erased and not used for research purposes.

Compensation

No monetary compensation for loss of time and inconvenience will be provided for your participation in this study.

Legal Rights

By accepting to participate in this study, you are not waiving any of your legal rights nor discharging the researchers or the institution, of their civil and professional responsibility.

Contact Information

You will be given a copy of the consent form to keep. If you have any questions or concerns regarding the research or your participation in it, either now or at any time in the future, please feel free to ask Dr. Rolando Del Maestro or Dr Nicholas Gelinas-Phaneuf, and they will be happy to answer any questions you may have. You can also communicate with the investigators at this address:

Dr Rolando Del Maestro

Montreal Neurological Institute and Hospital McGill University

3801 University St., Suite 109

Montreal, Quebec Canada H3A 2B4

rolando.delmaestro@mcgill.ca

Telephone: 514 398 5791 fax: 514 398 2811

If you have any questions regarding your rights as a research subject and you wish to discuss them with someone not conducting the study, you may contact the Montreal Neurological Hospital Patient Ombudsman at (514) 934-1934 ext 48306.

Summary of Research Results

Any published results of these studies can be mailed to you in reprint form if you are interested in knowing the findings.

Conflict of Interest

We have no known actual, apparent, potential or perceived conflicts of interest in conducting this study.

PARTICIPANT'S STATEMENT AND SIGNATURE

- By my signature to this consent form, I declare that this consent is given voluntarily under my own free will after sufficient time for consideration, and that I have completely understood the information regarding my participation in the study and have agreed to participate in the study.
- My signature to this Consent Form does not constitute a waiver of my legal rights or release the investigators, sponsor, or medical institutions connected with the study from their respective legal and professional responsibilities.
- I am free to withdraw from the study at any time with no penalty or loss of benefit to which I am otherwise entitled. During my continued participation I am entitled to request clarification or new information throughout the study, and the study neurosurgeon will make every effort to respond to my request.
- I agree to be contacted by a member of the Research Ethics Board of this hospital or the Quality Assurance Officer duly authorized by it, at their discretion.
- If I withdraw my consent, all my data will be erased and not used in the analysis.
- I will be given a copy of this document.

Check here if you allow the data from the *Global Assessment Tool for the Evaluation of Intraoperative Neurosurgical Skills* study to be used in this study.

I, ____________________________, (name of the participant), agree to participate in this study.

________________________________	__________________________	____________
Printed name of Participant (BLOCK CAPITALS)	Signature of the Participant	Date

INVESTIGATOR'S (OR DESIGNEE) STATEMENT AND SIGNATURE

I ______________________________ (name of physician or designee) received from the hospital's Research Ethics Board an approval to perform the clinical trial on human subjects in accordance with the accepted research ethics guideline. I hereby declare that I have fully explained the Consent Form to the patient.

______________________________	____________________________	__________
Name of the Investigator or Designee	Signature of the Investigator or Designee	Date

Appendix B

Personal Data Form

This form will remain confidential and will not be made public. The data entered here will serve for group stratification during the analysis of the data.

Name: ______________________________

Sex: **M** ☐ **F** ☐

Age: _______

You are a:

1) **Medical student** ☐
   a. Year in medical school: ______

2) **Neurosurgical resident** ☐ **:**
   a. **Level of training: PGY**_____
   b. **Fellow: Year of Fellowship:** _____
   c. **Approximate number of meningioma cases done:** _______

3) **Staff neurosurgeon** ☐ **:**
   a. **Years in practice:** ______
   b. **Area of specialty:** _______
   c. **Approximate number of meningioma cases done:** _______

4) **None of the above: Please specify:** ______

Does your occupation demand precise use of hands?

Continuously ☐ **Occasional** ☐ **Never** ☐

Handedness: **Right** ☐ **Left** ☐ **Ambidextrous** ☐

On average, how many hours per week do you play a musical instrument?

(Write 0 if you don't play an instrument): ___________

On average, how many hours per week do you play video games?

(write 0 if you don't play video games): ____________

Please specify the type of video game you play the most:

-First-person-shooter (e.g., Call Of Duty) ☐

-Sports (i.e. NHL 2011) ☐

-Real-time strategy (e.g., Starcraft) ☐

-Role playing (e.g., World of Warcraft) ☐

-Wii / XBOX Kinect/ PS3 move games ☐

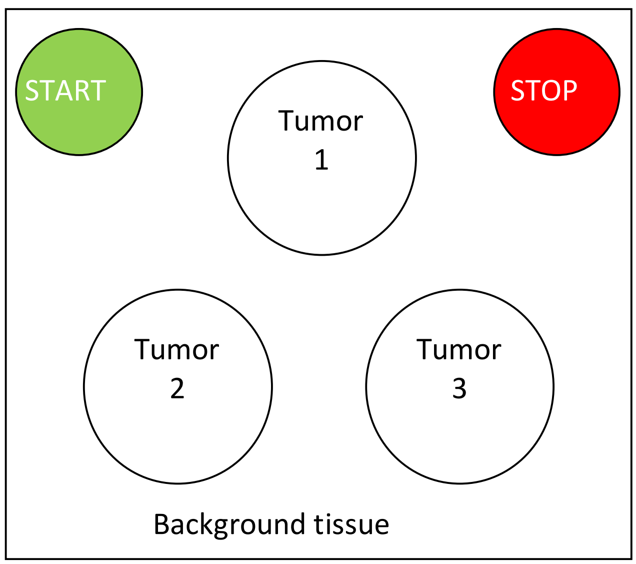
-Other (specify): ___________________

Thank you for your participation.

Appendix C

Instructions Form

You will be asked to go through 1 practice scenario and 6 test scenarios. In each scenario, you are asked to remove each of the three round tumors located on the top, lower left, and lower right of the screen (see figure below). These tumors should be removed using a tool that simulates the performance of a Cavitron Ultrasonic Surgical Aspirator (CUSA).



You will first be allowed one practice test run involving the removal of three simulated tumours to familiarize yourself with the test system.

Please perform the tasks according to the following directions.

1) **The tumors should be removed in a specific order:**
    a. **First, the upper tumor should be removed.**
    b. **Second, the lower left tumor should be removed.**
    c. **Third, the lower right tumor should be removed.**

2) **In order to start removing each tumor, first with the tip of the CUSA touch the green START button on the upper left of the screen. When you are done removing each tumor, with the tip of the CUSA touch the red STOP button on the upper right of the screen.**

3) **Please be careful to not accidentally touch the red STOP button before you are done with each tumor, as this exits the program without achieving the desired results.**

4) **You will be given three minutes to remove each tumour. If you have not finished removing the tumour in three minutes the system will stop automatically. You will be given a 1 minute rest after removing each tumour.**

5) **You can navigate the CUSA in the screen display and touch the tissues but the CUSA will remove the tissue only if it is activated by the pedal on the floor.**

6) **Each tumor should be removed as accurately as possible with minimal removal of the background tissue which surrounds the tumor.**

If you have any questions concerning the test please ask before starting.

Thank you for your participation.

Appendix D

Confirmation of Submission to Journal of Neurosurgery

JNS16-3038 Automaticity of Force Application during Simulated Brain Tumor Resection: Testing the Fitts and Posner Model manuscript received by J...

jneuro@msubmit.net <jneuro@msubmit.net>
Friday, December 2, 2016 at 3:52 PM
To: Abdulgadir Bugdadi

December 2, 2016

Dear Dr. Bugdadi,

Thank you for your submission entitled "Automaticity of Force Application during Simulated Brain Tumor Resection: Testing the Fitts and Posner Model" by Abdulgadir Bugdadi, Robin Sawaya, Duaa Olwi, Gmaan Al Zhrani, Hamed Azarnoush, Abdulrahman Sabbagh, Ghusn Alsideiri, Khalid Bajunaid, Fahad Alotaibi, Alexander Winkler-Schwartz, and Rolando Del Maestro JNS16-3038. It has now been received.

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