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Multitasking and Time Pressure in the Operating Room: Impact on Surgeons' Brain Function --Manuscript Draft--

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Dear Editor-in-Chief,

Thank you for providing us with an opportunity to revise our manuscript entitled **Multitasking and Time Pressure in the Operating Room: Impact on Surgeons' Brain Function** (ANNSURG-D-20-01211).

Authors: Hemel Narendra Modi, Harsimrat Singh, Ara Darzi, Daniel Richard Leff

The authors have worked to address the comments by the reviewer in an effort to make the manuscript more acceptable for publication in the *Annals of Surgery*.

The authors address each of the reviewer's comments in a point counter-point format below, and highlight the revisions made to the manuscript to make it easier for you and the editorial team to track the amendments we have made.

On behalf of all authors, I hope that as a result of the significant improvements made to the paper that the revised manuscript is more acceptable for publication.

The revised manuscript has been reviewed and approved by all authors, and on behalf of all authors I declare that this work has not been published previously, nor has it been considered for publication elsewhere.

Yours sincerely,



Mr Daniel R. Leff FRCS MS PhD
Reader in Surgery & Consultant Surgeon, Imperial College London

Reviewer Comment 1:

Nowhere in the paper or discussion is there mention of the type of training interventions that could possibly enable brain region recruitment. Nor is there any discussion in general on the practical implications of this work.

Authors' Response 1:

The reviewer makes an extremely valid point. We acknowledge the need to consider the wider impact on surgical training and practice, and specific interventions that could be employed to enhance brain function and improve surgical performance. Our findings highlight great potential application of neuroimaging assessments which will be of tremendous value to the surgical community in the future. With greater emphasis being placed on fostering non-technical skills among residents and on the human factors aspect of performance errors, brain behaviour assessments would be valuable as an adjunct to existing tools to determine if a resident is able to cope with the stresses of the OR and establish suitability for operative autonomy and independent practice.

As the reviewer quite rightly states, the value in assessing brain function is knowing what interventions can be employed to enhance prefrontal recruitment and improve performance under stressful conditions. A range of methods have been described in the non-medical domain, such as mental rehearsal, non-invasive brain stimulation, and biofeedback which have all been shown to improve motor and/or cognitive performance. There is, however, a paucity of research investigating their ability to improve performance in surgeons, nor has there been any investigation into their impact on prefrontal function. Similarly, we believe it is important to simultaneously appraise the barriers that must now be overcome before brain imaging is deployed in training programmes and surgical practice. These include the need for less obtrusive and lightweight systems that do not interfere with the surgical task, streamlining and automating data processing and analytical frameworks, and establishing the reliability and repeatability of neuroimaging as an assessment tool.

The potential application and limitations of utilising brain function assessments, as well as training interventions that may improve prefrontal engagement and performance are now addressed in greater depth in subsections within the discussion ('Applications in Surgical Training' and 'Future Directions & Stress Amelioration Strategies'; page 16, line 12–page 18, line 15). A summary Figure has also been included (Figure 5). As per the reviewer's suggestion, the 'Cognitive Processing' and 'Hormonal Inhibition' subsections have been shortened in order to accommodate this.

Reviewer Comment 2:

In the Limitations section of the paper...What is not addressed is how the participants viewed the secondary task. Was it a simple nuisance? Were the residents actively trying to divide their attention between two equally important tasks or did they think the secondary task was more important than the suturing task? In real life and in some of the highly cited research published by Stefanidis et. al on automaticity, attention and cognitive resources (which should be referenced in this paper), it may be acceptable to delay task progression for a few minutes to address important clinical questions. In addition, the reverse is also true. It may be important to address the clinical question after the operative task at hand is taken care of.

Authors' Response 2:

The reviewer highlights an interesting aspect of dual-task performance in terms of the way in which information is processed. We did not formally administer post-task questionnaires to determine how the participants viewed the imposition of the cognitive task. However, based on anecdotal verbal feedback from certain subjects, it was clear that there was variation in perception of the secondary task. Some less experienced participants reported slowing down (or even stopping) the motor task in order to attend to the decision-making scenario, whereas others reported delaying answering the decision-making task in order to prioritise completing the suturing.

Interestingly, these differences in how junior and senior residents handle dual-tasking is reflected in differences in prefrontal activation. Junior residents exhibit increased prefrontal activation in the highest workload condition (dual-tasking under time pressure) compared with other conditions (Supplemental Digital Content 8). In order to cognitively attend to multiple tasks demands simultaneously, allocation of processing resources to different brain systems is required in order to make decisions, plan responses, and implement actions in relation to each demand. However, the processing capacity of the human brain is limited and, if exceeded, has to be rationed to competing brain systems. It is conceivable that, during episodes of combined suturing and decision-making under temporal demand, junior residents are unable to cognitively attend to these multiple demands and therefore choose to engage in a single task and/or demand (i.e. 'selective attention'). In contrast, more senior trainees reported efforts in trying to continue suturing while answering the decision-making scenario and did not perceive that one hampered execution of the other. However, the prefrontal deactivation responses observed in this subgroup did not echo these

perceptions (Supplemental Digital Content 8). The 'divided attention' strategies employed by senior residents (as opposed to the 'selective attention' seen in junior residents) depend on recruitment of lateral prefrontal regions. Therefore, the deactivation patterns observed may represent a breakdown in the ability to attend to multiple competing stimuli simultaneously.

The differences in how junior and senior residents perceive handling the dual-tasking paradigm is now included in the main manuscript (page 16, lines 1–10). Furthermore, a discussion section has now been added to the Supplemental Digital Content which discusses the influence of expertise on prefrontal activation during dual-tasking scenarios (Supplemental Digital Content 10). As eluded to by the reviewer, we acknowledge that in the real OR surgeons may either stop operating to answer an important but case-irrelevant question or else ignore the question and continue with the procedure at hand especially if they are at a critical step. This methodological limitation has now been addressed in the revised manuscript (page 18, line 23–page 19, line 5).

Reviewer Comment 3:

The other, major question that should be addressed is whether most, many or any of the observations noted in this paper regarding prefrontal activation and deactivation are largely physiologic responses of the novice learner and will simply disappear with experience. Do the deactivation responses at the highest workload level for PGY 5's go away after a few years in practice?

Authors' Response 3:

Current data does not enable us to determine whether prefrontal deactivations will disappear after few years since in the current study we did not recruit attending surgeons with many years of independent experience. This notwithstanding, our previous study [Modi et al. Temporal Stress in the Operating Room: Brain Engagement Promotes "Coping" and Disengagement Prompts "Choking". *Annals of surgery* 267, 683-691 (2017)] showed that when placed under temporal stress, experienced subjects (which included attendings) were better able to maintain prefrontal engagement and stable performance compared with less experienced residents. Whilst this previous study did not impose a multitasking stressor on the subjects, it could be hypothesised that attending surgeons would demonstrate PFC activations (as opposed to the deactivation responses seen in residents in the current study) when attending to cognitive and motor demands simultaneously, reflecting appropriate tuning of attention and concentration when circumstances demand. This is now discussed in the new supplementary discussion (Supplemental Digital Content 10).

Reviewer Comment 4:

There were one or two areas with spelling errors or missing words.

Authors' Response 4:

The manuscript has been thoroughly re-read and spell-checked and any spelling and grammatical errors have been corrected.

MINI ABSTRACT

Surgeons experience multiple stressors in the operating room that can potentially disrupt technical performance. This functional neuroimaging study demonstrates that stress-induced performance deterioration among surgeons is associated with deactivation of brain regions important for attentional control, working memory and cognitive flexibility, particularly during tasks involving simultaneous motor and cognitive engagement.

STRUCTURED ABSTRACT

Objective: To assess the impact of multitasking and time pressure on surgeons' brain function during laparoscopic suturing.

Summary Background Data: Recent neuroimaging evidence suggests that deterioration in surgical performance under time pressure is associated with deactivation of the prefrontal cortex (PFC), an area important for executive functions. However, the effect of multitasking on operator brain function remains unknown.

Methods: 29 surgical residents performed an intracorporeal suturing task under four conditions: 1) self-paced suturing, 2) time-pressured suturing, 3) self-paced suturing plus decision-making, and 4) time-pressured suturing plus decision-making. Subjective workload was quantified using the Surgical Task Load Index. Technical skill was objectively assessed using task progression scores, error scores, leak volumes, and knot tensile strengths. PFC activation was measured using optical neuroimaging.

Results: Compared with self-paced suturing, subjective workload (au) was significantly greater in time-pressured suturing (146.0 vs. 196.0), suturing with decision-making (146.0 vs. 182.0), and time-pressured suturing with decision-making (146.0 vs. 227.0). Technical performance during combined suturing and decision-making tasks was inferior to suturing alone under time pressure or self-paced conditions ($p < 0.001$). Significant dorsolateral PFC (DLPFC) activations were observed during self-paced suturing, and ventrolateral PFC (VLPFC) deactivations were identified during time-pressured suturing. However, suturing in conjunction with decision-making resulted in

significant deactivation across both the VLPFC and DLPFC ($p < 0.05$). Random effects regression analysis confirmed decision-making predicts VLPFC and DLPFC deactivation ($z = -2.62, p < 0.05$).

Conclusions: Performance degradation during high workload conditions is associated with deactivation of prefrontal regions important for attentional control, working memory and cognitive flexibility, particularly during tasks involving simultaneous motor and cognitive engagement.

Original Paper Submission to Annals of Surgery (ASA Paper)
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Title of Manuscript

**Multitasking and Time Pressure in the Operating Room:
Impact on Surgeons' Brain Function**

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Running Head

Surgeon Stress and Brain Function

CONTRIBUTORSHIP

The study design was conceived and developed by HNM, HS, AD and DRL. HNM and HS executed the experiment and collected functional imaging data. Data pre-processing and statistical analysis was conducted by HNM, HS and DRL. Data interpretation was performed by HNM, HS and DRL in consultation with AD. The manuscript was drafted by HNM. Critical editing of the manuscript was performed by HS, AD and DRL.

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Conclusions: Performance degradation during high workload conditions is associated with deactivation of prefrontal regions important for attentional control, working memory and cognitive flexibility, particularly during tasks involving simultaneous motor and cognitive engagement.

INTRODUCTION

Surgery is a complex endeavor that requires considerable operator attention and concentration in order to maintain precise motor control and technical proficiency. However, the reality of the operating room (OR) is one in which the surgeon has to attend to multiple demands in addition to the primary surgical procedure. These extraneous factors, which include cognitive impositions (e.g. decision-making) and unforeseen technical challenges (e.g. intraoperative bleeding), compete for the surgeon's attention and may adversely impact upon the procedure at hand.¹ Indeed, observational studies have recorded distracting events occurring at an average rate of 13.6 times per case.² The compounding effects of multiple distractors can potentially disrupt surgical performance due to an operator's inability to allocate sufficient cognitive resources to each demand.³

⁴ In one qualitative study, surgeons regarded "full focus" and "distraction control" as important factors for performance excellence in surgery,⁵ whilst simulation studies demonstrate that intraoperative stress leads to reduced movement economy, increased technical errors, and longer task completion time.^{3, 4, 6}

Two common stressors experienced in the OR are time pressure (e.g. intraoperative bleeding) and multitasking (e.g. decision-making during an operative procedure). The ability to maintain performance under temporal load may relate to dynamic neural architectures in brain regions such as the prefrontal cortex (PFC), an area that subserves attention, concentration and top-down motor control.⁷ Data from non-medical fields suggests that an escalation in workload is associated with a progressive increase in prefrontal activation up to a critical maxima, beyond which any further increase in workload (or overload) leads to prefrontal deactivation and disengagement from the

task.⁸ Our previous work demonstrated prefrontal attenuation and deterioration in technical performance when residents laparoscopically suture under temporal demand, a phenomenon more pronounced in junior than senior residents.⁹ Whilst this study provided valuable insights into the relationship between expertise, technical performance and brain function under stress, only one stressor (time pressure) was evaluated. The effect of several concurrent stressors, more representative of an OR environment, has not been delineated and hence the impact on operator brain function remains unknown. Nonetheless, studies have shown an increase in task completion time, errors, and instrument pathlength when surgeons are distracted by a secondary cognitive task during a laparoscopic procedure.^{6, 10, 11} Evidence from non-medical fields highlights that simultaneous execution of motor and cognitive tasks results in diminished prefrontal activation and motor performance deterioration.^{12, 13} This implies that motor-cognitive multitasking may disrupt executive centers in the brain resulting in a loss of attention, task disengagement and performance deterioration. However, whether similar changes in brain function occur in surgeons multitasking in the OR is yet to be investigated.

The aim of this study was to compare surgeons' PFC responses during a laparoscopic suturing exercise performed under a temporal demand, a cognitive demand, and both temporal and cognitive demands concurrently. We hypothesised that suturing under time pressure will lead to attenuated prefrontal responses but suturing in the presence of a concurrent cognitive task will lead to greater and more widespread deactivation of the PFC along with more substantial performance decline.

METHODS

Subjects

Following local ethical approval (LREC: 05/Q0403/142) and having obtained written informed consent, 29 surgical residents (PGY1-5+) enrolled in the study (median age [range]=33 [29-57] years, 9 females). All participants were screened for handedness and were requested to abstain from alcohol and caffeine intake for 24 hours prior to participation.

Task Paradigm

Participants performed a laparoscopic intracorporeal suturing exercise on a box trainer (iSim2, iSurgicals, UK). The task involved closing a 2cm defect in a Penrose drain by inserting a 2-0 Vicryl® suture (Ethicon, Somerville, NJ) as close as possible to pre-marked entry and exit points on either side of the defect and tying a knot by formulating one double throw followed by two single throws of the suture (Figure 1).

All subjects performed the task under four experimental conditions: (1) 'single-task': laparoscopic knot-tying with no time limit, (2) 'single-task under time pressure': laparoscopic knot-tying with a two-minute per knot time restriction, (3) 'dual-task': laparoscopic knot-tying with no time limit whilst simultaneously responding to clinical decision-making scenarios, and (4) 'dual-task under time pressure': laparoscopic knot-tying with a two-minute per knot time restriction whilst simultaneously responding to clinical decision-making scenarios. Participants performed the task five times under each experimental condition with a 30-second inter-trial rest period between each knot. The order in which the subjects experienced the conditions was randomized.

Clinical Decision-Making Scenarios

The purpose of the decision-making scenarios was to impose a realistic cognitive demand during the laparoscopic suturing task. The scenarios were vignettes of acute surgical patients typically encountered during an on-call shift. The vignettes were pre-recorded and played at the same stage during the suturing task for each subject. The participants were required to listen to the scenario whilst they continued suturing and to give a response as to how they would manage the patient. Two surgical attendings with a combined independent practicing experience of 32 years rated the “difficulty” and “authenticity” of each scenario on a scale of 1-10 to ensure internal consistency and face validity of all vignettes. Inter-rater reliability was tested using intraclass correlation (difficulty: 0.891 [95% CI 0.747 – 0.956], $p < 0.01$; authenticity: 0.835 [95% CI 0.629 – 0.931], $p < 0.01$). The internal consistency of the clinical vignettes with respect to difficulty and authenticity was determined using the Cronbach’s alpha test (both > 0.9).

Outcome Measures

The ETG-4000 Optical Topography System (Hitachi Medical Corp., Japan) was used to measure activation across 24 prefrontal cortical locations (*‘channels’*), the positions of which were defined according to the international 10-20 system of probe placement (Figure 1 & Table 1).¹⁴ The Surgical Task Load Index (SURG-TLX) questionnaire was used to evaluate subjective workload (au). Heart rate (HR) was continuously recorded using a portable electrocardiogram (Bioharness, Zephyr Technology, Annapolis, Maryland). Technical skill was objectively assessed using four performance parameters as described previously: Task Progression Score (TPS; au), Error Score (ES; mm), Leak Volume (LV; ml), and Knot Tensile Strength (KTS; Newtons, N) (Figure 1).⁹

Data Processing and Statistical Analysis

Statistical analysis was performed using SPSS version 23.0 (IBM Corp., Armonk, NY). A threshold of $p < 0.05$ was deemed statistically significant. The Kolmogorov-Smirnov test demonstrated that SURG-TLX, HR, technical performance and HbO₂ data deviated significantly from a normal distribution ($p < 0.05$). Accordingly, data was analyzed using non-parametric tests of significance.

Subjective Workload, Heart Rate and Technical Skills Data

Between-condition comparisons of SURG-TLX, HR and performance metrics were analyzed using the Friedman test with *post hoc* Wilcoxon Signed Rank test. The association between subjective workload (SURG-TLX) and technical performance was determined using a Pearson correlation.

Functional Neuroimaging Data

Optical data was pre-processed using a customised MATLAB-based toolbox (HOMER2).¹⁵ After application of a low-pass filter (0.5Hz) to minimise high frequency noise and electrocardiographic effects on the data, 45/696 channels were excluded from statistical analysis due to inadequate optical signals (data rejection rate=6.5%). Remaining channel data was detrended to correct for baseline fluctuations and block averaged to increase the signal-to-noise ratio. Raw mean intensity values were converted to changes in optical density relative to the mean of each channel across the whole task period. Channel-wise motion detection and spline correction were performed. Relative changes in light intensities were converted into changes in HbO₂ concentration using the modified Beer-Lambert Law.¹⁶

Cortical Haemodynamic Data

For each condition, channel activation was determined by comparing the mean baseline rest HbO₂ data sampled over 10 seconds before task onset (HbO_{2Rest}) with mean task HbO₂ data sampled over 100 seconds starting 10 seconds after task onset (HbO_{2Task}) using the Wilcoxon Signed Rank test. Channels displaying a statistically significant ($p < 0.05$) increase in HbO₂ were considered '*activated*', and those demonstrating a significant decrease in HbO₂ were considered '*deactivated*' (Figure 1). For each channel and each haemoglobin species, a new variable ΔHbO_2 was computed (HbO_{2Task} minus HbO_{2Rest}). ΔHbO_2 in each channel was compared between conditions using the Friedman test and *post hoc* Wilcoxon Signed Rank tests.

Random Effects Model

In order to account for the clustering of cortical haemodynamic data that occurs in a repeated measures experimental paradigm, a random effects regression model (REM) was employed to further appreciate the influence of the stressor (e.g. time pressure, decision-making, or both) on ΔHbO_2 . REM was carried out using Stata version 14 (StataCorp, College Station, TX).

Subgroup Analysis

To appreciate expertise-related differences in perceived workload, motor performance and brain function, subjects were further subdivided into expertise groups (Supplemental Digital Content 1). Subjective workload, technical performance and prefrontal cortical haemodynamic data were compared between experimental conditions within each subgroup, and between groups within each experimental condition (Supplemental Digital Content 2).

RESULTS

Subjective Workload and Heart Rate

Compared with the single-task condition, SURG-TLX scores were significantly greater when single-tasking under time pressure (median [IQR]: 146.0 [129.0] vs 196.0 [141.0]; $z=-4.270$, $p<0.001$), dual-tasking (146.0 [129.0] vs 182.0 [115.0]; $z=-4.022$, $p<0.001$), and dual-tasking under time pressure (146.0 [129.0] vs 227.0 [116.0]; $z=-4.595$, $p<0.001$). Furthermore, SURG-TLX scores were significantly greater when dual-tasking under time pressure compared with single-tasking under time pressure (196.0 [141.0] vs 227.0 [116.0]; $z=-4.180$, $p<0.001$) and dual-tasking without time pressure (182.0 [115.0] vs 227.0 [116.0]; $z=-4.236$, $p<0.001$) (Figure 2A, Table 2). There was no significant between-condition difference in heart rate ($p=0.543$).

Technical Skills

TPS was significantly inferior when dual-tasking under time pressure compared with single-tasking ($z=-5.456$, $p<0.001$) and dual-tasking alone ($z=-5.135$, $p<0.001$). Furthermore, TPS was significantly inferior when dual-tasking compared to single-tasking under time pressure ($z=-4.554$, $p<0.001$), and when single-tasking under time pressure compared with single-tasking alone ($z=-5.240$, $p<0.001$) (Figure 2B, Table 2).

LV was significantly greater in the single-task under time pressure condition compared with the single-task condition alone (median [IQR]: 23.7ml [2.1] vs 13.6ml [3.0]; $z=-4.704$, $p<0.001$). Furthermore, significantly greater LV was identified in the dual-task under time pressure condition compared with dual-task (27.3ml [4.4] vs 18.1ml [2.0]; $z=-4.704$, $p<0.001$), single-task under time pressure (27.3ml [4.4] vs 23.7ml [2.1]; $z=-4.574$,

$p < 0.001$), and single-task only conditions (27.3ml [4.4] vs 13.6ml [3.0]; $z = -4.703$, $p < 0.001$). Finally, LV was greater in the dual-task condition compared with the single-task condition (18.1ml [2.0] vs 13.6ml [3.0]; $z = -4.606$, $p < 0.001$), but less than the single-task under time pressure condition (18.1ml [2.0] vs 23.7ml [2.1]; $z = -4.705$, $p < 0.001$) (Figure 2C, Table 2).

Although no significant between-condition differences were observed in KTS ($\chi^2(3) = 4.591$, $p = 0.204$), there was a trend towards weaker knots being tied in dual-tasking conditions (Figure 2D, Table 2). There were no significant between-condition differences in ES ($\chi^2(3) = 3.820$, $p = 0.282$) (Figure 2E, Table 2).

Performance Correlation Analysis

There was a significant negative correlation between SURG-TLX score and TPS ($r = -0.171$, $p < 0.001$), and a significant positive correlation between SURG-TLX and LV ($r = 0.327$, $p < 0.001$). However, there was no significant correlation between SURG-TLX and ES ($r = 0.008$, $p = 0.856$) or KTS ($r = 0.005$, $p = 0.903$).

Prefrontal Activation

During the single-task condition, a significant task-related increase in HbO₂ was evident in channels located in the bilateral dorsolateral prefrontal cortex (DLPFC) (Figure 3). In contrast, a significant decrease in HbO₂ was observed during the single-task under time pressure condition in channels located in the bilateral ventrolateral prefrontal cortex (VLPFC) (Figure 3). Moreover, a significant HbO₂ decrease occurred across the bilateral

DLPFC and VLPFC when dual-tasking without time pressure. A similar but non-significant change in HbO₂ concentration occurred when dual-tasking with time pressure (Figure 3). HbO₂ concentration change (ΔHbO_2) was significantly less ($p<0.05$) in both dual-tasking conditions compared with single-tasking conditions in the bilateral DLPFC and VLPFC (Figure 4, Supplemental Digital Content 3).

Random Effects Regression

Multivariable analysis demonstrated that dual-tasking independently predicts a significant decrease in ΔHbO_2 when controlling for time pressure and task block in the bilateral DLPFC and VLPFC (channels 7, 12, 21 & 23) ($z=-2.62$, $p<0.05$) (Supplemental Digital Content 4A). However, time pressure did not predict a significant change in ΔHbO_2 within any prefrontal region when controlling for the presence of decision-making and task block (Supplemental Digital Content 4B).

Subgroup Analysis

Among PGY1-2 and PGY3-4 residents, SURG-TLX scores increased with task demands ($p<0.05$), whereas no significant between-condition difference in perceived workload was observed amongst PGY5+ residents (Supplemental Digital Content 5-6 & 7A). Significantly inferior progression was identified in high workload conditions amongst PGY1-2 and PGY3-4 residents (both $p<0.05$), but not among PGY5+ residents (Supplemental Digital Content 5-6 & 7B). PGY1-2 and PGY3-4 residents exhibited prefrontal deactivation during lower workload conditions, and typical activation responses at the highest workload level (Supplemental Digital Content 5 & 8A-B). In

contrast, PGY5+ residents showed sustained prefrontal activation during the lowest workload conditions, and deactivation responses only at the highest workload level (Supplemental Digital Content 5 & 8C).

DISCUSSION

Surgeons performed a laparoscopic suturing task under temporal and cognitive demands in order to assess the effect of time pressure and multitasking on technical performance and brain function. In the absence of any additional demands, laparoscopic suturing was associated with significant activation of the DLPFC. However, in the presence of temporal stress deactivation responses were observed in the VLPFC along with performance deterioration, whereas suturing while engaging with a decision-making task (dual-tasking) led to deactivation in both the DLPFC and VLPFC and even greater decline in technical performance.

Stress and Surgical Performance

One of the challenges of safe surgical practice is the integration of technical and cognitive skills for performance success. However, unexpected events can transpire during an operation placing excessive mental demands on the surgeon and jeopardizing technical performance.¹⁷ Indeed, our data demonstrates that laparoscopic suturing under a temporal and/or cognitive demand negatively affects operative ability; specifically, suturing while engaging with a decision-making task leads to a greater decline in performance compared with suturing under time pressure. These findings are supported by Moorthy et al⁶ who found that a greater number of technical errors were committed with multitasking compared with a time pressure condition during a laparoscopic transfer task.⁶ Others have also reported the negative effect of decision-making, multitasking, and case-irrelevant conversations on task completion time and movement economy during minimally invasive surgery.^{3, 11, 18} Evidently attending to different demands simultaneously in the OR can have a substantial effect on motor performance.

However, the neurophysiological basis for such significant performance decline has, until now, not been investigated.

Psychological Perspective

The psychological literature offers insights into the mechanisms of stress-induced performance decline observed in the current study. The '*distraction-conflict*' model of performance posits that stressful conditions create a distracting environment which can shift the operator's attention away from the primary task and onto task-irrelevant cues such as consequences of failure.¹⁹ During tasks which rely on working memory capacity, workload-induced cognitive distractions compete for working memory resources that are required for optimal performance.²⁰ Accordingly, there is a failure to inhibit the cognitive effects of distracting stimuli and an individual is unable to maintain focus on the primary task, a phenomenon known as '*directed attention fatigue*'.²¹ It is feasible that when dual-tasking, residents were unable to inhibit the distracting effects of the decision-making task resulting in a loss of engagement on the suturing task and performance degradation. This model would suggest that an ability to maintain stable performance in the OR during stressful conditions is dependent on intact functioning of executive centers in the brain.⁷ Unlike prior literature, the current study utilized optical neuroimaging to delineate more precisely the functional changes in executive brain centers that accompany distraction-conflict and the decline in operative performance.

Neurophysiological Mechanisms of Performance Decline

When performing a laparoscopic suturing task under calm self-paced conditions, residents exhibited significant activation responses in the DLPFC. Since lateral PFC regions are important for attention and resilience against distracting events,^{22, 23} the

responses observed are indicative of enhanced attentional control and task engagement. However, residents demonstrated deactivation in the VLPFC when suturing under time pressure and in both the DLPFC and VLPFC when dual-tasking. Similar deactivations have been observed by others in spatially comparable brain regions.²⁴⁻²⁷ For example, Al-Shargie et al²⁴ observed that receiving negative feedback whilst performing a mental arithmetic task under time pressure led to a decrease in HbO₂ concentration in the right VLPFC.²⁴ Similar decreases in HbO₂ concentration were observed in the DLPFC during working memory tasks,²⁵ mental arithmetic,²⁶ and video gaming.²⁷ Indeed, our previous work also demonstrated deactivation responses within the VLPFC and DLPFC among surgical residents operating under temporal demand.⁹ The DLPFC is important for motor planning,²⁸ decision-making,²⁹ and attention;²² whereas the VLPFC is critical for vigilance and resistance to environmental distraction.²³ Thus, the deactivation responses observed in the current study might represent a degree of mental ‘overload’ in which executive function is disrupted,²⁹ attentional control is lost, and technical performance suffers.³⁰

Whilst both time pressure and dual-tasking led to deactivation responses and decline in technical performance, the effect was greater in dual-task conditions. The deterioration in performance on one or both tasks in a dual-task paradigm is known as ‘*dual-task interference*’.³¹ The underlying mechanisms of dual-task interference relates to competition of limited attentional resources³² or information-processing neural pathways,³³ both of which rely on the integrity of the central executive system.³⁴ In line with our findings, other brain imaging studies have confirmed a loss of prefrontal function in dual-task paradigms which would explain performance degradation in one or both tasks.^{12, 13}

Although post-task feedback was not formally collected, junior residents reported “slowing down the suturing task in order to respond to the clinical scenario” or “delaying answering the scenario until suturing was complete”. In contrast, senior residents reported efforts to complete both tasks simultaneously and felt that “one task did not hamper execution of the other”. Interestingly, this anecdotal evidence is supported by the difference in prefrontal processing observed between junior and senior residents when dual-tasking (Supplemental Digital Content 8). Junior residents appear to utilize selective attention strategies, whereas more experienced subjects employ a divided attention approach, both of which, in this case, fail to sufficiently stabilize technical performance (see Supplemental Digital Content 10 for further discussion on subgroup results).

Application in Surgical Training

There is enormous potential to use the findings from this study to improve surgical training and performance which will inevitably be advantageous to patient safety. Given the known limitations of relying solely on markers of technical performance,^{35, 36} assessment of brain behavior can provide a more holistic evaluation of resident capability with specific focus on workload and attention. Deriving neurophysiological benchmarks provides objective evidence of residents’ ability to maintain attention and concentration under the stressful conditions of the OR and can supplement other tools such as FLS and Verification of Proficiency checklists upon which decisions are made about progressive responsibility, operative autonomy, and board certification.³⁷ For example, Shetty et al³⁵ demonstrated that despite some residents attaining expert FLS benchmarks of performance they were investing on average 4 to 5 times more prefrontal attentional resources than attendings.³⁵ In terms of skills assessment, attenuated prefrontal responses during tasks performed under relatively calm conditions would indicated skill

automaticity, whereas an increase in prefrontal activation during times of stress would reflect an ability to appropriately invest greater attentional resources in order to stabilize surgical performance (Figure 5). A resident who attains these benchmarks may be suitable to progress towards practicing independently. However, these clinical applications are of course contingent on overcoming key barriers to the use of neuroimaging technology in everyday practice (Figure 5).

Future Directions & Stress Amelioration Strategies

The stress-related changes in brain function observed among residents highlight the need to develop training interventions that facilitate prefrontal recruitment, enhance task engagement, and improve performance under pressure. A range of performance-enhancing interventions have been investigated, predominantly in non-surgical fields, for their ability to help individuals preserve or improve psychomotor skill (Figure 5).

Mental rehearsal is the cognitive rehearsal of a task without overt physical movement to produce genuine sensory experiences.³⁸ It is the most widely investigated mental skill in performance psychology and has been shown to improve surgical performance by helping operators mentally prepare for a procedure, focusing their attention on critical steps of an operation and anticipating complications.^{39,40}

Transcranial direct current stimulation (tDCS) uses direct electrical currents to non-invasively stimulate specific brain regions. In a recent meta-analysis, tDCS was found to improve reaction time, execution time and force of contraction during upper limb motor performance.⁴¹ In the wider community, tDCS has been investigated for its potential to enhance performance in fields such as sports⁴² and music⁴³, and mitigate the detrimental

effects of sustained attention on performance by modulating prefrontal activity and increasing the availability of attentional resources.⁴⁴

Biofeedback is the process of measuring surrogate markers of arousal (e.g. heart rate variability) and visualizing them in real-time to increase the subject's awareness of the effect of his or her actions, thoughts and emotions on physiological states.⁴⁵ Biofeedback may reduce stress-induced physiological arousal and mitigate the associated negative effects on technical performance. Heart rate variability biofeedback systems, for example, improve athletic performance⁴⁶ and executive functions⁴⁷, and reduce perceived stress and anxiety.⁴⁸

Although these interventions have demonstrable performance benefits in non-surgical domains, there are a lack of studies investigating their use in surgery and whether they improve performance and/or positively impact surgeons' neurophysiology when multitasking in the real OR remains unknown.

Limitations

Although time pressure and decision-making mirror realistic stressors in the OR, the current study was conducted in a controlled laboratory environment to prevent the influence of confounding factors and enable a block-design experiment to be conducted. Whilst this setting may not have been as realistic as a fully immersive simulated operating theatre, the trends in SURG-TLX scores suggest subjects experienced a genuine sense of temporal urgency and escalating cognitive demand. In reality, when faced with both motor and cognitive demands, most surgeons would either slow down or stop executing the primary motor task in order to answer a clinical question if it were deemed important

and/or urgent. Alternatively, if a critical stage of a procedure has been reached responding to a case-irrelevant question is delayed for a few moments. The task paradigm utilized in this study in which participants were instructed to answer a clinical question and continue suturing simultaneously may not reflect such attentional selectivity strategies employed in the real OR.⁴⁹ Exposing subjects to high workload conditions, may have induced a sympathetic-driven increase in HR, resulting in artificially greater prefrontal haemodynamic responses.⁵⁰ However, no significant between-condition differences in HR were observed suggesting that the prefrontal responses represented genuine cognitive processes rather than systemic stress responses. Furthermore, high workload conditions elicited a decrease in prefrontal oxygenation which cannot be explained by confounding systemic effects. The subjects' responses to the decision-making scenarios were not recorded and scored. However, in this study answering a scenario served as a clinically relevant distractor to the primary suturing task rather than forming part of the performance assessment *per se*. Furthermore, answers to clinical vignettes can be challenging to validate as there can be multiple acceptable answers.

CONCLUSION

Surgical residents maintain prefrontal activation and task engagement when operating under calm conditions. However, at higher workloads prefrontal deactivation occurs and there is a disruption in executive function leading to a deterioration in technical performance. This is particularly apparent when residents are required to simultaneously attend to motor and cognitive stimuli.

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FIGURE LEGENDS

FIGURE 1. A, Prefrontal cortical activation is measured using functional near-infrared spectroscopy in which an array of near-infrared light emitters and detectors are positioned over the scalp according to the international 10-20 system of probe placement. The banana-shaped photon path (yellow crescent) that travels from an emitter to an adjacent detector forms a data channel (Ch). Absorption of light within each of the 24 prefrontal channels provides an indication of local haemodynamic changes in the cortical tissue which, in turn, serves as a surrogate marker of cortical activation. B, (i) A typical cortical activation response is characterised by a task-induced increase in oxygenated haemoglobin (HbO₂) and/or a smaller amplitude decrease in deoxygenated haemoglobin (HHb). (ii) An inactive channel shows no significant changes in HbO₂ or HHb concentration in response to a stimulus. (iii) Conversely, channel deactivation is depicted as a decrease in HbO₂ and/or an increase in HHb. C, Technical performance metrics (i) Task progression score (au) – each task episode was assigned a score based on task progression, with 1 point awarded for each of the following steps: (1) mounting the needle onto the needle holder, (2) needle insertion into the drain, (3) exiting the needle from the drain, (4) double throw, (5) 1st single throw, and (6) 2nd single throw of a laparoscopic reef knot. The task progression score comprised the total number of points obtained during the task (maximum score=6). (ii) Error score (mm) – adapted from the Fundamentals of Laparoscopic Surgery scoring system for intracorporeal suturing and calculated as follows: Error Score = [Distance (mm) between needle insertion point and pre-marked target position + Distance (mm) between needle exit point and pre-marked target position]. (iii) Leak volume (ml) – saline was infused through each drain at a rate of 150 drops/minute controlled via a digital pump. The volume of saline leaking from the closed defect over a 1-minute period was recorded to assess the quality of defect closure.

(iv) Knot tensile strength (N) – a bench-top tensiometer (5565 single-axis tensiometer, Instron, UK) was used to quantify the tensile strength of every tied knot.

FIGURE 2. Subjective workload (SURG-TLX) score (A), task progression score (B), leak volume (C), knot tensile strength (D) and error score (E) in each experimental condition. Error bars represent the interquartile range. * $p < 0.05$

FIGURE 3. Task-induced changes in HbO₂ concentration in the prefrontal cortex in each experimental condition. Channels in which there was an increase in HbO₂ from baseline demonstrate patterns of '*activation*' (red), and channels in which there was a decrease in HbO₂ demonstrate '*deactivation*' (blue). Channels in which there was a statistically significant change ($p < 0.05$) in HbO₂ concentration are circled black, highlighting *activated* and *deactivated* channels.

FIGURE 4. Comparison of Δ HbO₂ between conditions. Channels in which Δ HbO₂ is significantly less ($p < 0.05$) in dual task compared with single task conditions are highlighted (blue). Channels in which there are no significant changes in Δ HbO₂ and are provided for spatial reference (white).

FIGURE 5. Potential applications and limitations of utilizing functional brain imaging in surgical training and practice. *Left Panel:* Evaluation of how brain behaviour could be used in the assessment of skill acquisition. When executing a discrete technical task under self-paced conditions, attending surgeons with many years of experience demonstrate

attenuated prefrontal responses suggesting skill internalisation and automaticity. Residents exhibit increased prefrontal activation indicative of greater attentional resource allocation due to their conscious awareness of task performance and the need to maintain concentration. When multitasking and/or operating under temporal demand, experienced surgeons possess the cognitive bandwidth to improve attention on a task by increasing prefrontal engagement. However, residents will demonstrate attenuated or inverted prefrontal responses possibly reflecting failure of executive functioning. For assessment purposes, critical cortical haemodynamic thresholds would need to be determined which might guide resident progressive autonomy and decisions for independent practice. *Middle Panel:* Performance-enhancing interventions that may aid recruitment of prefrontal brain regions, enhance task engagement, and improve performance under stressful conditions include (A) non-invasive brain stimulation, (B) mental rehearsal, and (C) heart rate variability (HRV) biofeedback training. *Right Panel:* Current barriers to implementing functional neuroimaging in surgical skills assessment include heavy and obtrusive hardware, complex data analysis requiring off-line labor-intensive data processing, and the need to establish reliability and repeatability of results in real OR settings. Finally, objectively measuring cognitive state in order to assess suitability for career progression may have considerable ethical implications which must be reconciled before deployment within surgical training programmes can be considered.

LIST OF SUPPLEMENTAL DIGITAL CONTENT

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Supplemental Digital Content 8.pptx

Supplemental Digital Content 9.pptx

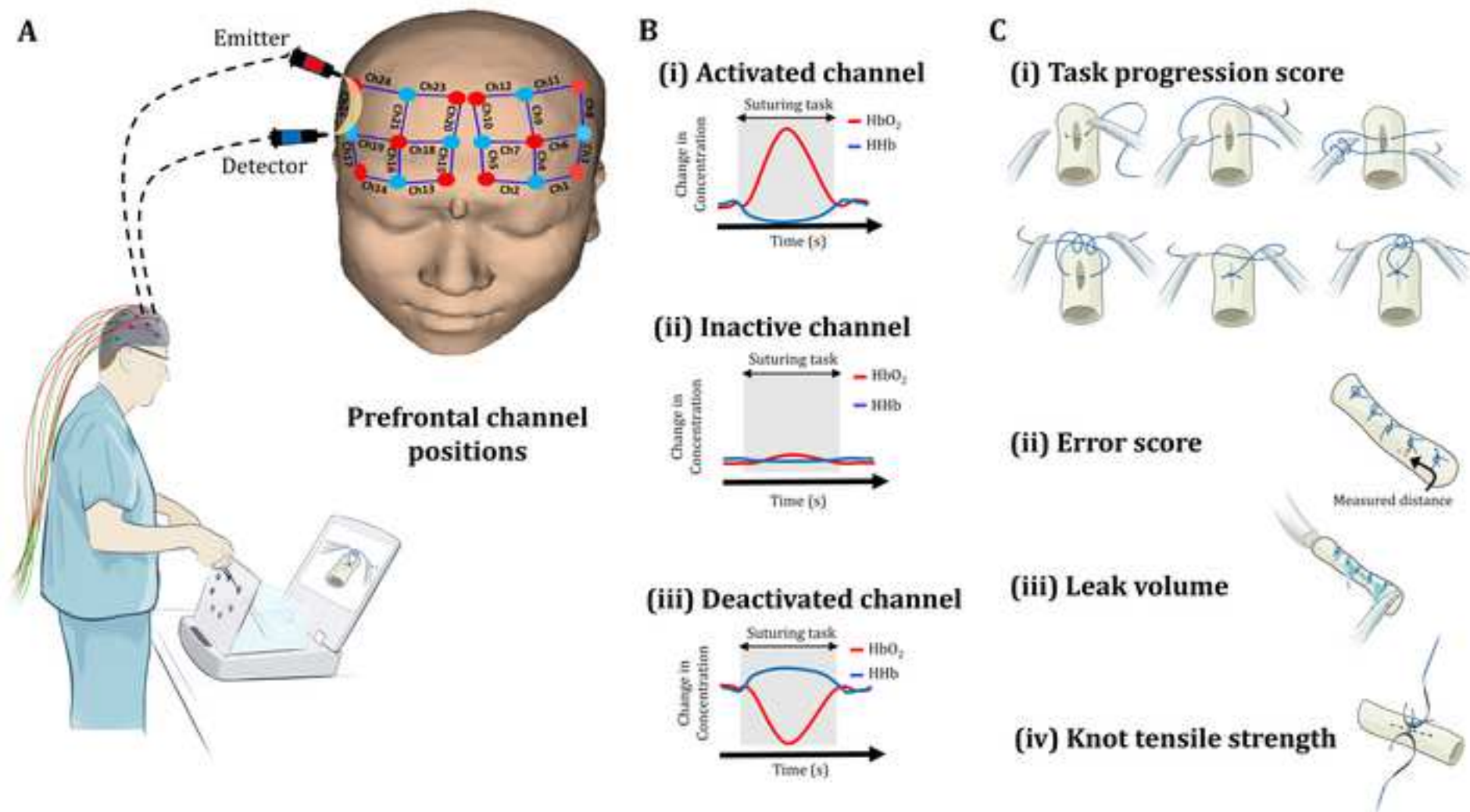
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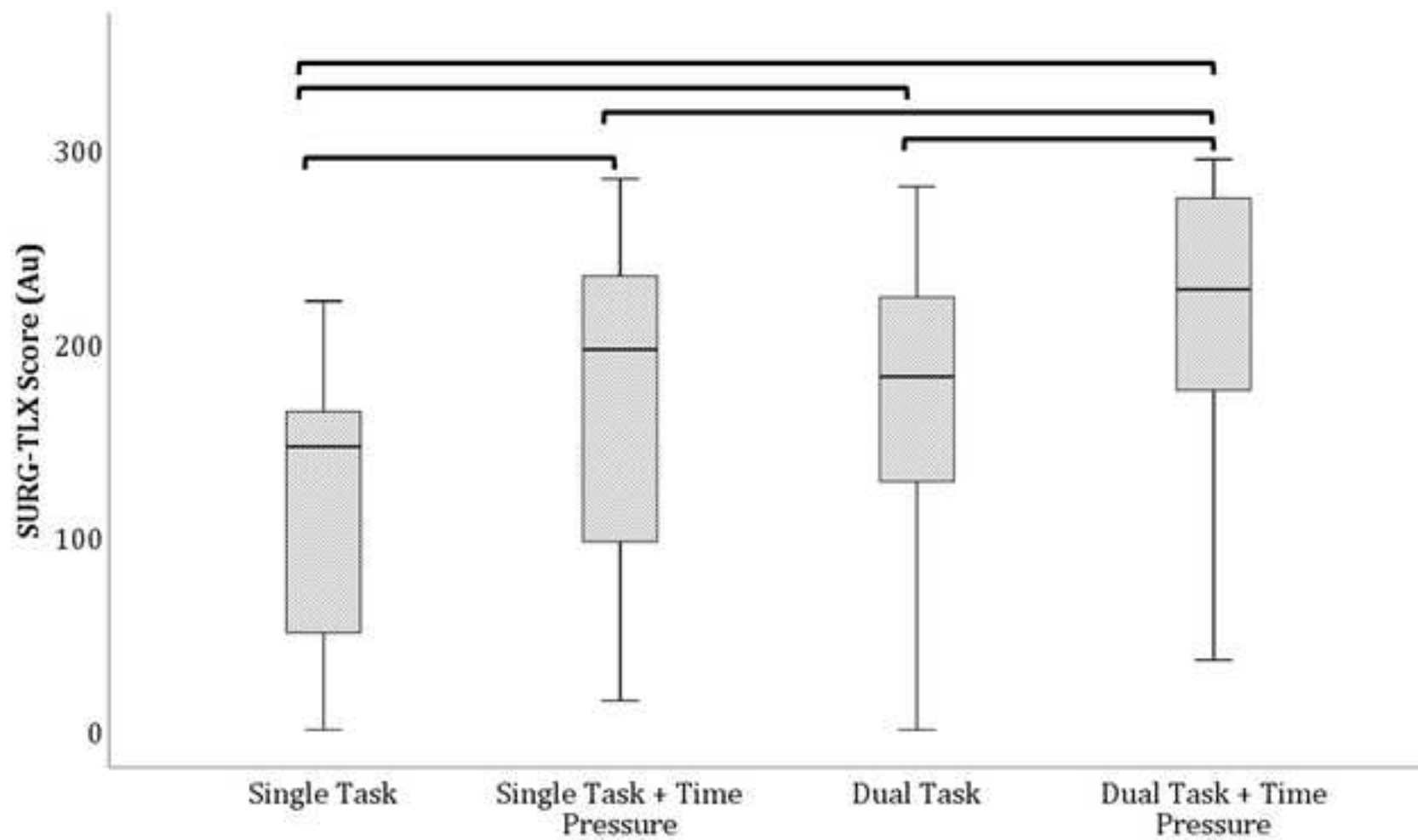
Table 1

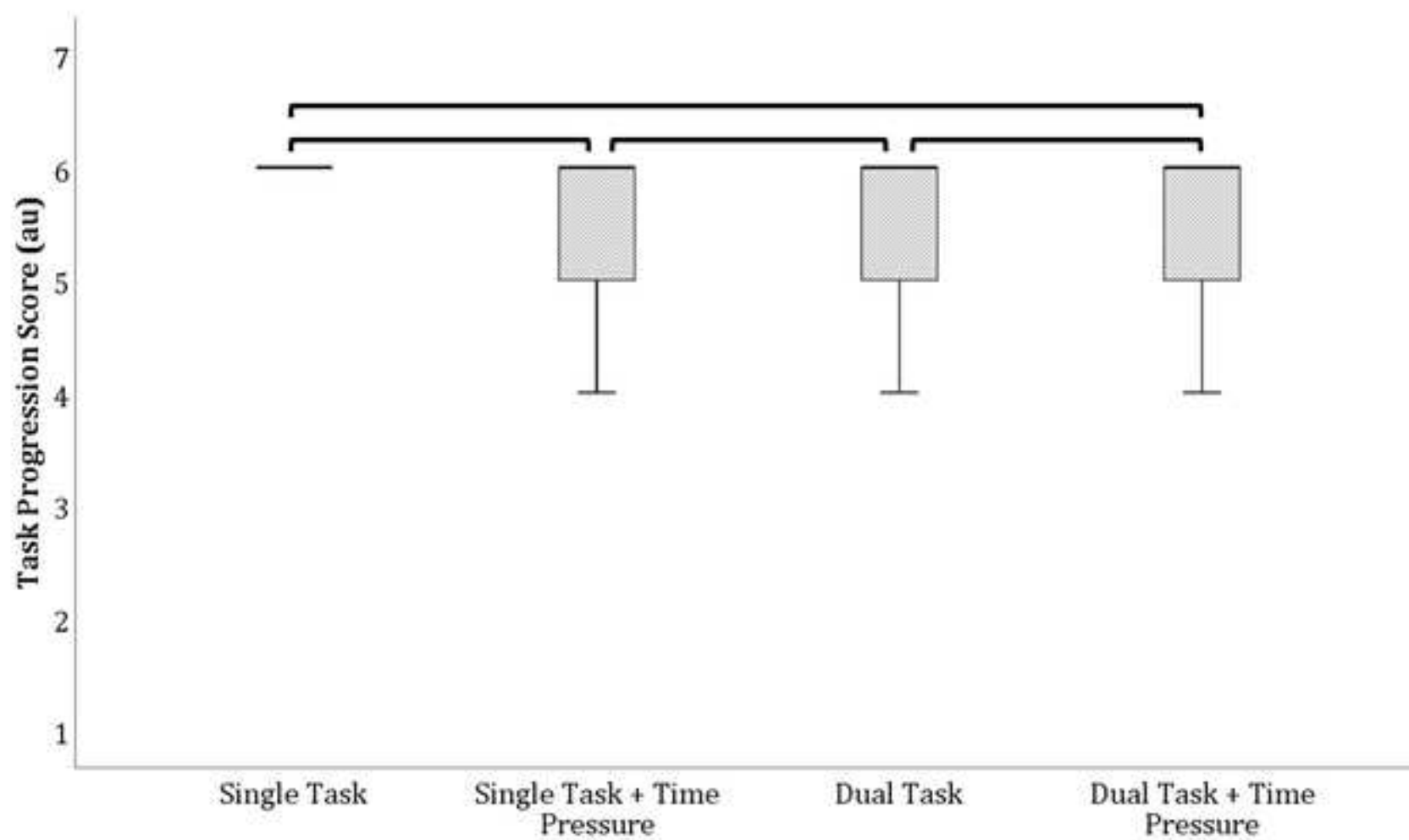
TABLE 1. Prefrontal channel locations				
Emitter	Detector	Channel	Gyrus	Prefrontal Subregion
1	1	1	Left Inferior Frontal (Pars Triangularis)	Left Mid-VLPFC
1	2	2	Left Superior Frontal	Left Dorsomedial PFC
2	1	3	Left Inferior Frontal (Pars Triangularis)	Left Mid-VLPFC
2	3	4	Left Inferior Frontal (Pars Triangularis)	Left Mid-VLPFC
3	1	5	Left Superior Frontal	Left Dorsomedial PFC
3	2	6	Left Inferior Frontal (Pars Triangularis)	Left Mid-VLPFC
3	3	7	Left Superior Frontal	Left Dorsomedial PFC
3	4	8	Left Inferior Frontal (Pars Triangularis)	Left Mid-VLPFC
4	2	9	Left Inferior Frontal (Pars Triangularis)	Left Mid-VLPFC
4	4	10	Left Superior Frontal	Left Dorsomedial PFC
5	3	11	Left Inferior Frontal (Pars Opercularis)	Left Posterior-VLPFC
5	4	12	Left Superior Frontal	Left Dorsomedial PFC
6	5	13	Right Inferior Frontal (Pars Triangularis)	Right Mid-VLPFC
6	6	14	Right Inferior Frontal (Pars Triangularis)	Right Mid-VLPFC
7	5	15	Right Middle Frontal	Right DLPFC
7	7	16	Right Inferior Frontal (Pars Triangularis)	Right Mid-VLPFC
8	5	17	Right Inferior Frontal (Pars Opercularis)	Right Posterior-VLPFC
8	6	18	Right Middle Frontal	Right DLPFC
8	7	19	Right Inferior Frontal (Pars Triangularis)	Right Mid-VLPFC
8	8	20	Right Middle Frontal	Right DLPFC
9	6	21	Right Inferior Frontal (Pars Triangularis)	Right Mid-VLPFC
9	8	22	Right Precentral	Right Primary Motor Cortex
10	7	23	Right Inferior Frontal (Pars Triangularis)	Right Mid-VLPFC
10	8	24	Right Inferior Frontal (Pars Opercularis)	Right Posterior-VLPFC
VLPFC: ventrolateral prefrontal cortex; DLPFC: dorsolateral prefrontal cortex				

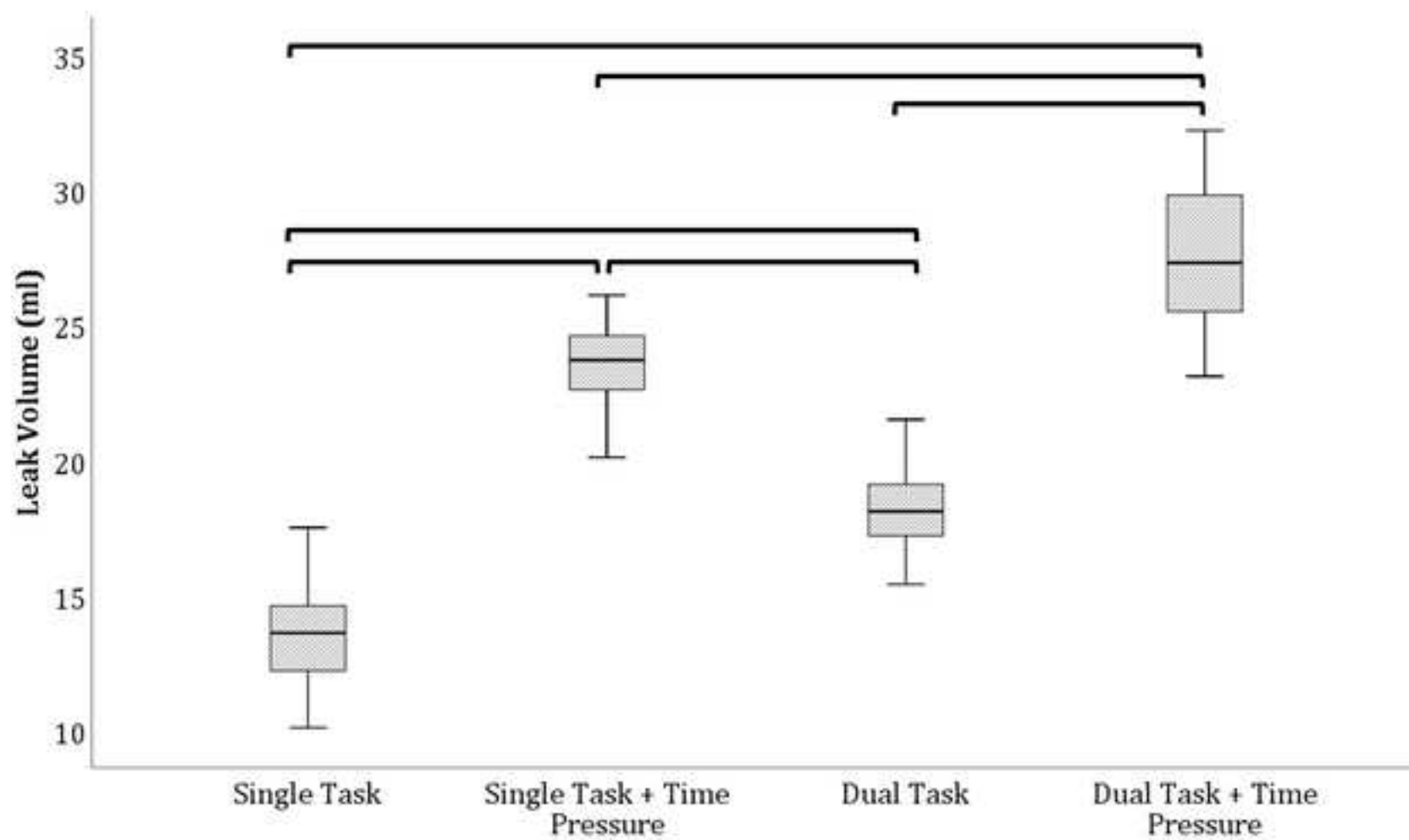
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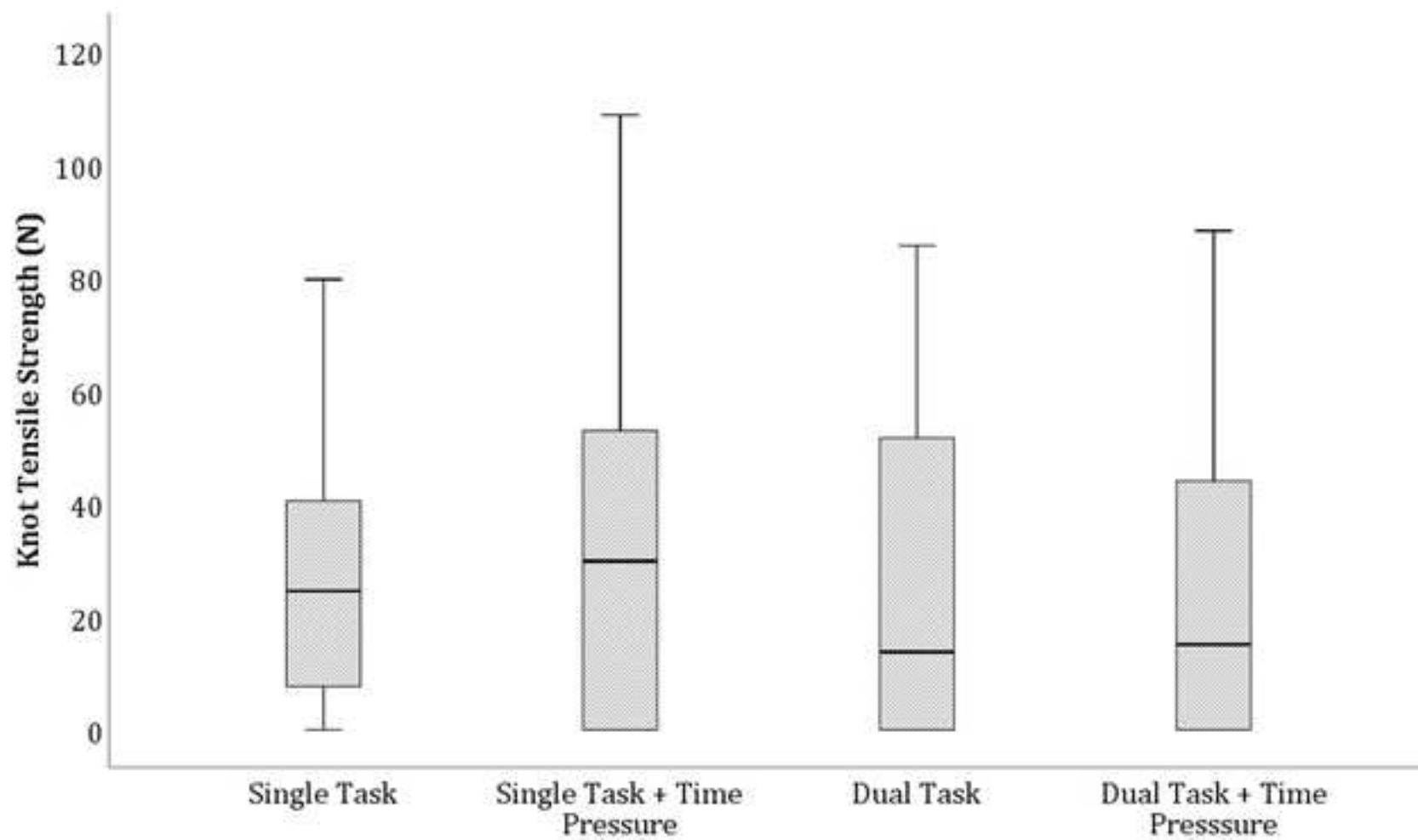
TABLE 2. Subjective Workload and Technical Performance					
Condition	SURG-TLX (au)	Task Progression Score (au)	Error Score (mm)	Leak Volume (ml)	Knot Tensile Strength (N)
Single Task	146.0 (129.0)	6.0 (0.0)	3.0 (3.0)	13.6 (3.0)	24.5 (33.1)
Single Task + Time Pressure	196.0 (141.0)	6.0 (1.0)	3.5 (5.5)	23.7 (2.1)	29.8 (53.7)
Dual Task	182.0 (115.0)	6.0 (1.0)	3.0 (3.5)	18.1 (2.0)	13.7 (52.3)
Dual Task + Time Pressure	227.0 (116.0)	6.0 (1.0)	3.5 (4.5)	27.3 (4.4)	15.1 (45.6)
SURG-TLX: Surgical Task Load Index; au: arbitrary units; mm: millimetres; ml: millilitres; N: Newtons. Data are median values (IQR).					

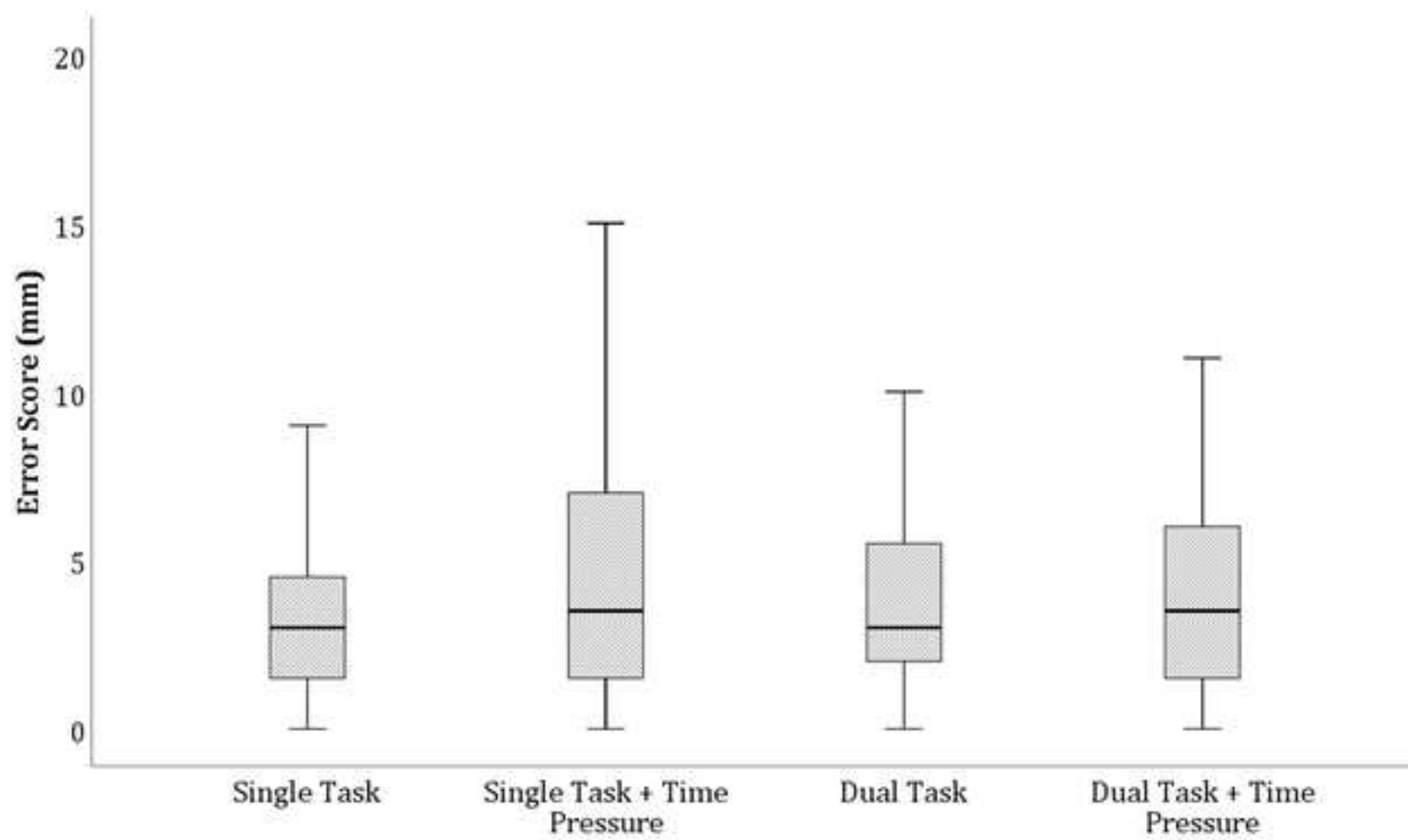


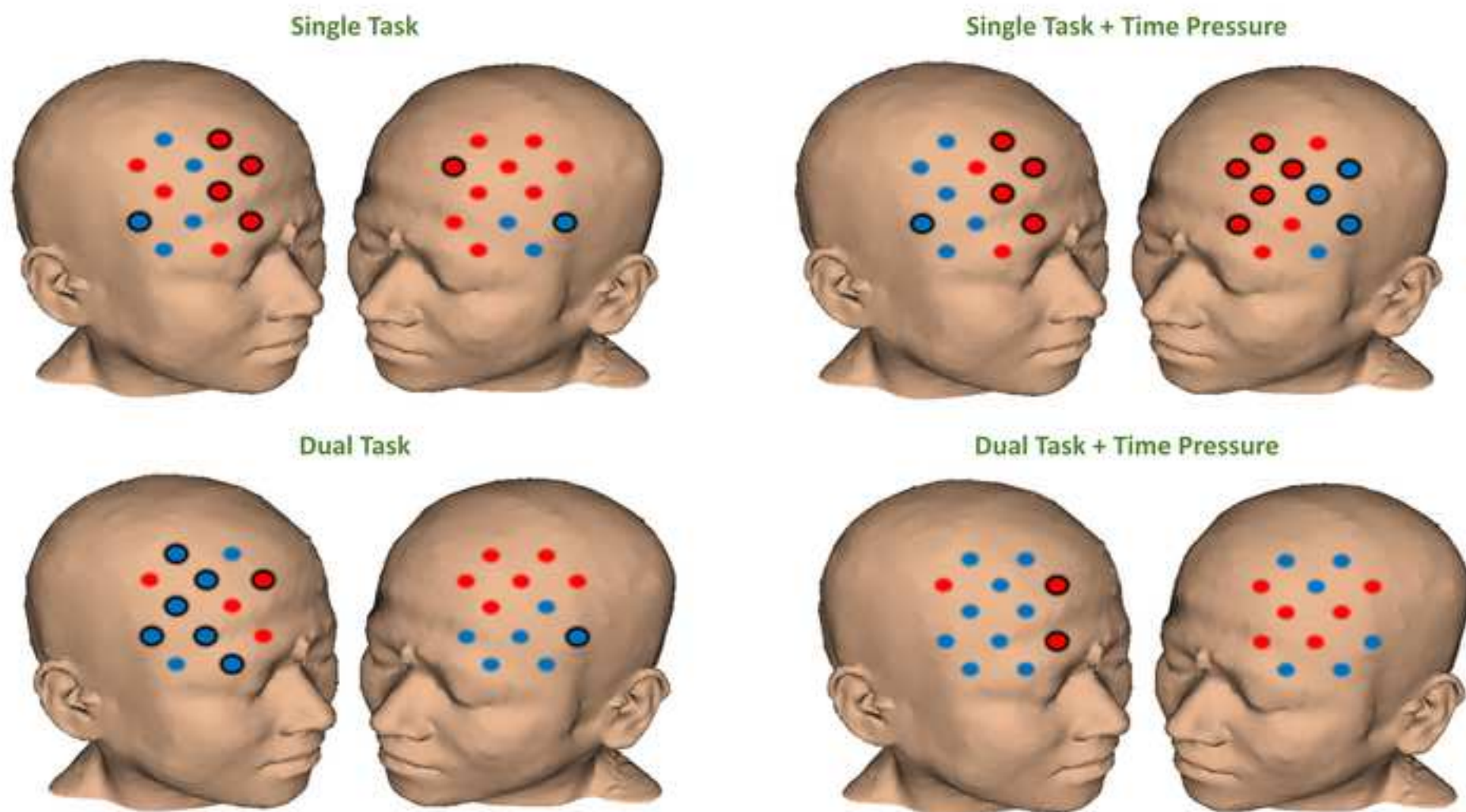


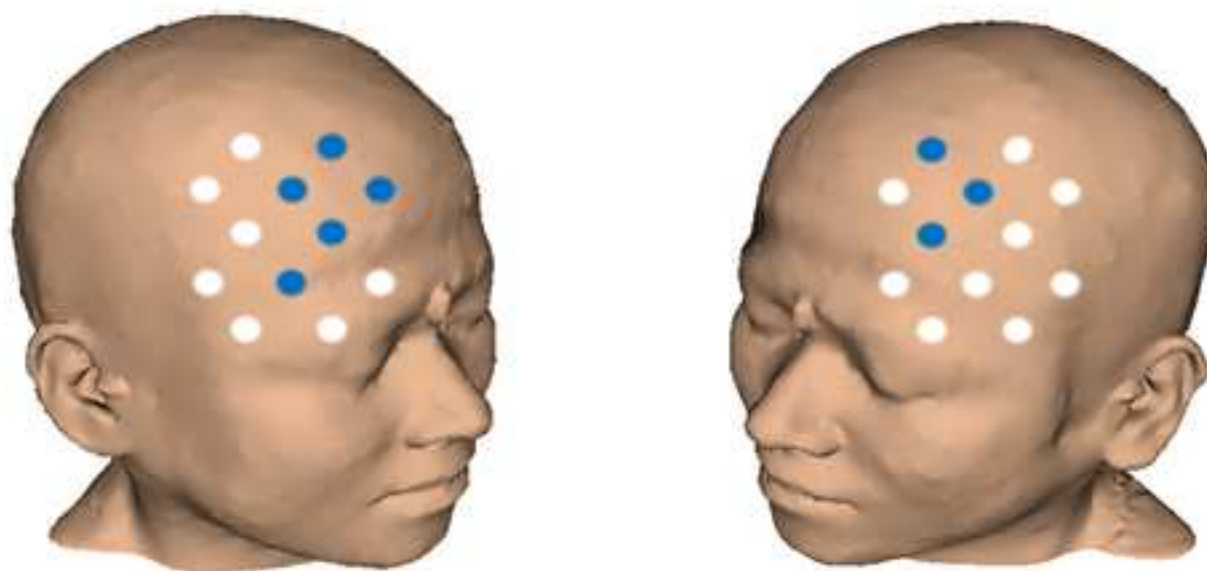


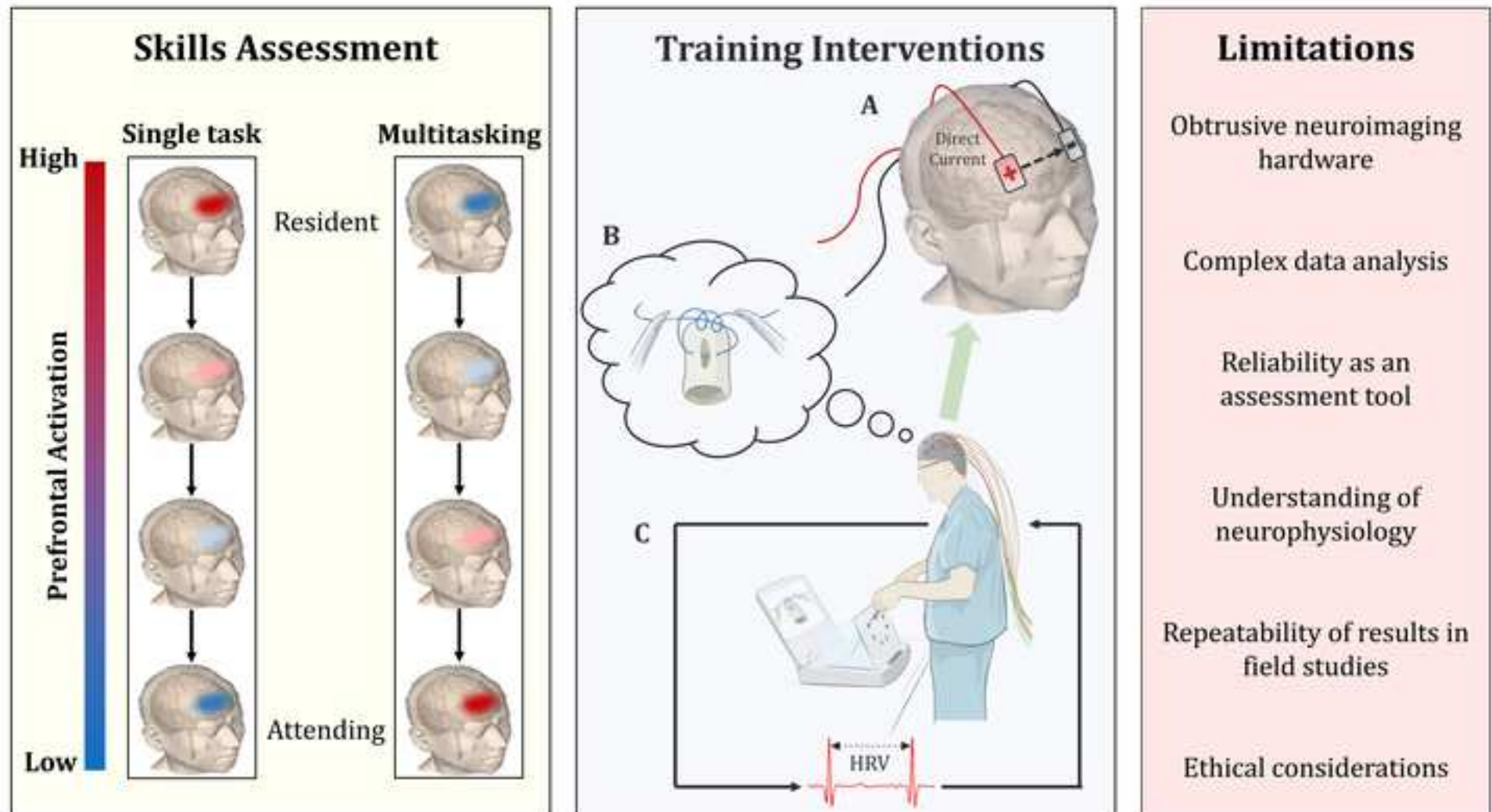


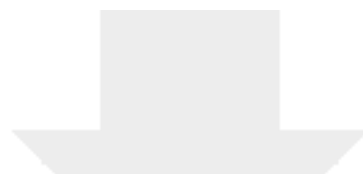








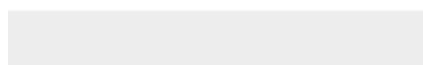
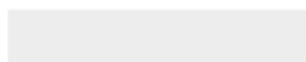


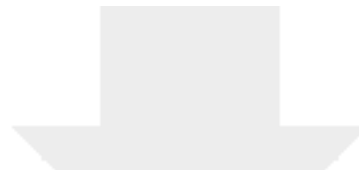


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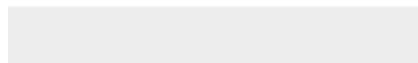
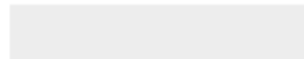


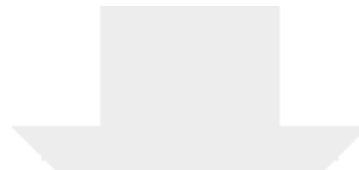


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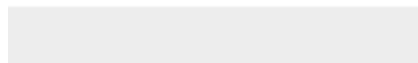
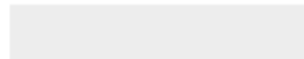


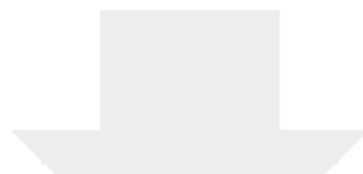


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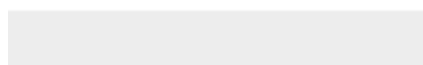
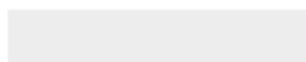


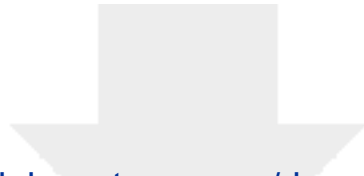


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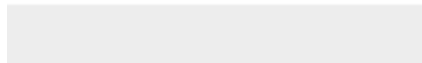


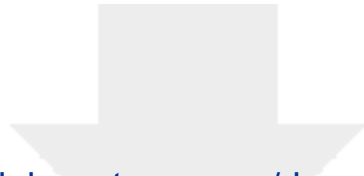


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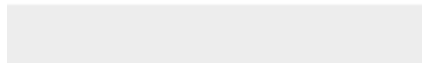


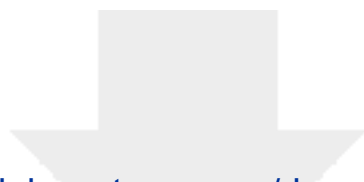


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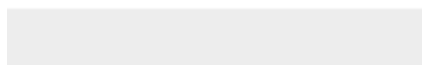
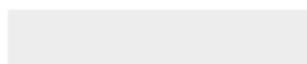


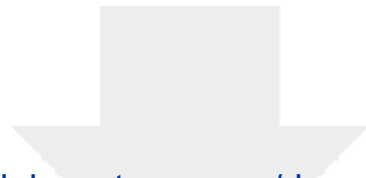


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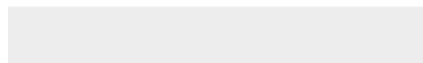
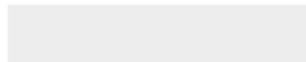


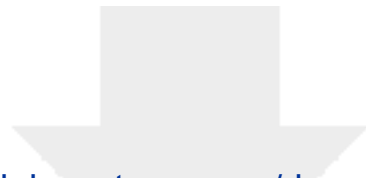


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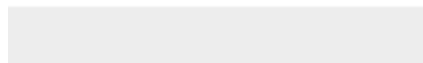
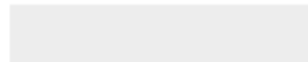


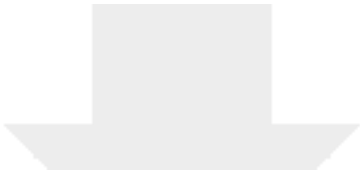


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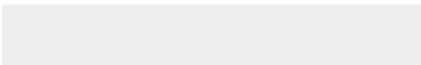
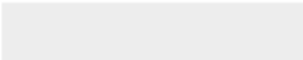




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