Decision making during preoperative surgical planning.

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Running Head: Pre-operative Surgical Planning

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Abstract

Objective: This study concerns the analysis of decision-making during pre-operative surgical planning, and the measure of the impact of expertise and surgical case complexity through the definition of cognitive indicators: conflict and cognitive control. **Background:** Planning is a critical stage in naturalistic decision-making and there is some evidence suggesting that this activity depends on the level of expertise, and task demands. Cognitive Engineering allows for envisaging surgery as a control task performed by the surgical work system on patient body work domain. The specificity of surgery resides in the necessity to cope with (potential) conflicts between the intervention purposes of the surgical work system, and biological laws governing the patient body. **Method:** 6 neurosurgeons (two board-certified neurosurgeons, two chief-residents, and two residents) described the operative procedure envisaged on 9 surgical cases of increasing surgical complexity. In details, we analyzed one surgical case described by one expert. Moreover, we measured the number of conflicts and controls reported by each surgeons. **Results:** Two experts were the only ones for which the report of conflicts increased with surgical complexity (respectively 75% and 73% of the conflict variance predicted by complexity). The two experts significantly activated a higher proportion of knowledge-based control (resp. 43% and 38%) than intermediates and residents. The residents significantly activated more motor-skill based controls (resp. 40% and 44%) than intermediates and experts. **Conclusion:** It seems that expert surgical decision-making to cope with task demands is significantly associated with conflict monitoring. Knowledge-based control to regulate conflict is privileged by experts. **Application:** conflicts and controls analyzed through verbal reports can be used as relevant indicators to highlight critical moments in decision-making potentially requiring assistance from information systems.

INTRODUCTION

For a long time, medical decision-making was envisaged through psychological

models based on a normative approach involving an optimal solution and biases studied in

laboratories (Abernathy & Ham, 1995; Elstein & Schwarz, 2002). Today, the Natural

Decision Making (NDM) framework envisaged medical decision-making as included in a

natural setting (Patel *et al*., 2002; Klein & Zambok, 1997). Surgery particularly satisfies the

criteria defining naturalistic decision making, i.e. ill-structured problems, uncertain dynamic

environment, competing goals, action/feedback loop, time stress, high stakes, multiple

operators and organisational norms (Farrington-Darby & Wilson, 2006). NDM researches

showed that to cope with these constraints, planning constitutes an important step. The

detection of a problem at an early stage improves timely and effective regulation (Klein *et al*.,

2005). During the planning stage in the aviation domain, flight pilots anticipated the potential

risks and regulations which needed to be activated to keep control of the process (Amalberti

& Deblon, 1992). In the medical domain, Xiao et al. (1997) showed that anaesthetists planned

some Points For Consideration (PFCs). These PFCs led to activating knowledge and using

rules that enable to regulate the problem, to prepare action and to configure material

assistance.

Some evidence suggests that experts are particularly able to foresee potential failures

or risks and to envisage their regulation. Experts would be particularly able to mentally

simulate how a situation will develop, and see antecedents and consequences of the course of

action (Endsley, 1995; Hoc & Amalberti, 2007; Hutton & Klein, 1999). During an

experimental simulation of work situation, Randel and Pugh (1996) showed that contrary to

novices, expert electronic warfare technicians formed complex models of potential situations

and saw potential conflicts of rules driving their activity. Flin *et al*. (2007) interviewed

surgeons on their assessment of a situation and their decision on how to cope with it. They concluded that situation assessment and switching between decision methods to cope with potential problems depends on the level of surgical expertise and task demands.

One fundamental issue posed by these studies concerns the operational definition of detected problems that (potentially) interfere with activity. More precisely, concerning surgical decision-making, the question is how a problem can be concretely defined and tracked in the surgeon's decision-making process?

Cognitive Engineering can help us to answer to this question. The Cognitive Engineering framework underlines that work system is fundamentally a functional entity that controls a domain of work (Rasmussen, 1986; Vicente, 1999). In their work system, the anaesthetists mainly perform a supervision task requiring the monitoring of a set of biological parameters (Gaba, 2000; Seagull & Sanderson, 2001). In this scope, it is relevant to define potential problems as points requiring attentional resources (Points For Consideration) during the monitoring task (Xiao *et al.*, 1997). But in surgery work systems, surgeons rather perform a concrete intervention on the patient body, modifying it with irreversible transformations (Darzi & Mackay, 2006). Even though the patient body is a domain requiring surgical control, the intervention process (for instance in neurosurgery, to remove a tumor, to clip an aneurism) is inherently *in conflict* with the laws governing the patient body (e.g. body integrity, tissues maintained in life, stable physiological balances), which are based on self-regulatory processes maintaining the biological stability of the internal environment (Lind, 2003; Miller, 2004). The notion of conflict had already been used to describe problems in surgery emerging from contradictory goals (Cook & Woods, 1994; Young *et al.*, 2007). More generally, Hettinger *et al.* (1998) proposed to consider the surgical work system as a strike environment. Thus, we will define a conflict in surgery as a problem involving a contradiction between the

purposes and resources engaged by surgical work system, and work domain constituted by the patient body, its biological states, functions, structures, and properties.[1]

During an intervention, the surgical work system must maintain the control of the work domain, and so, must regulate the conflict that can be potentially envisaged or suddenly emerged in the operation room. Cognitive control allows the regulation of conflict (Botvinick *et al.*, 2001). In Cognitive Engineering, the SRK model of cognitive control proposed by Rasmussen (1986) differentiates three control levels.

- Skill-based behaviour involves a control based on the sensory-motor loop.

- Rule-based behaviour involves a control based on rules constructed from previous experiences and giving the conditions in which an operation can be performed.

- Knowledge-based behaviour involves a control based on a conceptual model allowing an analysis of the environment and purposes to attain.

Rasmussen (1986) suggested that when confronted with a problem, an expert operator who is initially situated at the skill level of cognitive control would migrate to knowledge-based control. The latter level of control implies higher cognitive processes to understand the situation and to cope with its higher demands. But, this hypothesis was validated neither in surgery nor in other domains.

The objective of this study was firstly to evaluate the possibility of building indicators to elicit surgical conflicts and their controls from verbal protocols of surgeons during practice of pre-operative neurosurgical planning. We also wished to provide first results on the possible impact of surgical expertise on conflicts and controls along with surgical case complexity. Our final purpose is to tackle cognitive indicators of decision-making, representing critical moments requiring assistance from information systems.

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1 Note that conflict can appear from contradictions inside the surgical work system, between the work system purposes and work system resources, for instance, if equipment does not work. This kind of conflict was not observed in the descriptions of pre-operative planning procedures.

METHOD

Participants

We asked 6 neurosurgeons (5 men, 1 woman; 34.5 years old ± 7.5) to describe the procedure they would adopt to operate on 9 neurosurgical cases with increasing surgical complexity.

Variables and procedure

The surgeons had different levels of expertise in neurosurgery and included: two residents (two years of residency), two intermediates (chief-residents), and two experts (board-certified neurosurgeons) from the same academic neurosurgical department. One of the expert neurosurgeons was considered as a referent. As a first step, he selected 9 surgical cases he had personally operated more than one year before the study. He classified these cases according to two criteria of surgical complexity: the anatomical location and the histopathology of the lesion (Table 1). For each case, he provided a file including clinical data (i.e. sex, age, hemispheric dominance, antecedents, history and symptoms), anatomical location and histopathology of the lesion, and relevant neuroimaging data (CT scan and MR images). A post-hoc classification of these clinical cases by another expert (board-certified neurosurgeon), following the same procedure validated the first ordering.

The 6 surgeons were asked to detail how they would go about the 9 surgical cases as in preoperative planning. The different stages of the session were as follows: (i) *Study of the clinical case:* the neurosurgeon examined the patient file. (ii) *Verbal report of the surgical procedure:* the neurosurgeons described the procedure that they would plan to remove the lesion. No time limitation was imposed during the session. The interviewer made no intervention interfering with the verbal report. The surgeon was placed in front of a microphone and a computer, which automatically recorded the verbal report. Each surgeon

did not process more than three clinical cases per day. The order of processing followed the degree of case complexity from lower to higher in order to insure a gentle progression in difficulty for residents. None of the participants, including the referent expert, had prior information about the theoretical premises of the study and the way in which verbal protocol would be processed. Finally, verbal fluency was measured to assess its impact on the number of cognitive items extracted.

Measurement

Linguistic units representing conflicts and cognitive controls were extracted from each verbal report describing the surgical procedure stage. A conflict was negatively referred as an assertion that was not a pure description of the surgical procedure. Positively, a conflict involved an explicit or implicit contradiction between the surgical work system and work domain. Explicit conflict corresponded to linguistic formulations about a problem, worry, or difficulty that the surgeon would have to cope with, like *"There will be a difficult portion..."* . But sometimes, surgeons directly reported a control from which an underlying conflict could be inferred, like from the following skill-based control: *"I perform the craniotomy and I am careful not to open the frontal sinus…"* . In this example, the conflict was "craniotomy *versus* presence of frontal sinus". Implicit conflicts were then explicitly formulated by the analysts to check that it had not been already coded. A cognitive control was defined as a regulation process aimed at solving the conflict. Our coding of cognitive controls followed an extended version of the SRK approach in which we distinguished five levels of control. *Skill (S)* based control was coded as the implementation of a perceptual or motor process respectively divided into *Perceptual Skill* (Sp) and *Motor Skill* (Sm) based controls *(*Sp: *"Careful not to extend the dissection to far behind"; Sm: "I dissect...")*. *Rule (R)* based control corresponded to a conditional control of the conflict (e.g. *"While I am working inside the tumor, bah. ... I*

am relatively safe." or "*After performing the craniotomy, I polish the bone edges if there is somme bleeding at this level*".). If some conditions are satisfied, then an operation can be done. This operation can be a skill, knowledge or use of assistance. To avoid a non mastered recursion, we coded only a rule and not its components. *Knowledge (K)* based control referred to concepts or reasoning relying on a deep understanding of the conflict foundations (e.g. *"If we damage the mix nerves, swallowing disorders could occur postoperatively."*). *Assistance (A)* based control involved the use of external resources for conflict regulation, such as patient images or surgical staff advice (e.g. *"to give some steroids to the patient to decrease intracranial pressure"*.). Several controls and several control levels can be activated for a single conflict. Below, we present an extract of data coding. Verbalizations were embedded in tags (in bold font, **<...>**data**</...>**) describing the nature of the data (non-conflict, conflict and content of the conflict, SRK&A cognitive controls). It concerns a part of the exeresis phase explained by Resident 1 for the folder 10:

<non-conflict> Also up, take a cleavage **</non-conflict><C5 control Sm>**and move well **</C5 control><C5 conflict "excision versus tissues around">** around the tumor once **</C5 conflict><C6 control 1 Sm>** Do not rely too much **</C6 control 1><C6 conflict: excision versus presence of left temporal lobe>** on the left temporal lobe, **</C6 conflict><C6 control 2 K>** because this patient is right, to avoid language disorders **</C6 control 2>**

In a first stage, two clinical cases (i.e. twelve verbal reports) randomly chosen were independently coded by two analysts. Inter-rater agreement was moderate for conflicts (Cohen-Kappa test, K=0.43), and excellent for cognitive controls (K=0.83). To compensate for moderate agreement on conflict coding, all the clinical cases were coded jointly by two analysts. Disagreements about items were discussed and solved. The two analysts had backgrounds in cognitive psychology and verbal data coding. They had been trained in neurosurgery during one and half year through the reading of documents in neuroanatomy,

multiple observations in operative rooms, and interviews and debriefings with an expert neurosurgeon (the referent expert).

Statistical Methods

Note that before quantitative analysis of data, we described the qualitative analysis of a verbalization made by an expert about a simple surgical case (folder 2). The presentation of the content of non-conflict, conflicts and cognitive control should permit to understand clearly how conflict and control can be inserted in the course of the description of surgical procedure. Due to our small participant sample, effect of expertise on cognitive items (number of conflicts, controls, distinct control levels per conflict) and verbal fluency (number of words) was assessed through a non-parametric analysis of variance (Kruskall-Wallis test). Correlations between these variables and surgical complexity were assessed with a non-parametric rank correlation test (Tau-b of Kendall). Individual stepwise linear regression was used to measure the contribution of verbal fluency and surgical complexity to the variability of cognitive items. We added the number of conflicts per case in the regression model in order to predict the number of cognitive controls mentioned. It was assumed in our regression models that the nine case files followed an interval scale representing degrees in surgical complexity. Distribution of control level frequencies was evaluated using the chi-square test and 95% Confidence Intervals (CI).

RESULTS

Qualitative Analyses

Table 2 presents the semantic content of non-conflictual and conflictual items found in the surgical procedure described by Expert 2 for the surgical case n°2. This verbal protocol involved conflicts with all the kinds of cognitive control that we differentiated (Sm, Sp, R, K,

& A based control). We noticed that the order of items followed the surgical stages of the procedure. The first nine items were non-conflictual descriptions of the procedure. The first two items concerned the preparation phase: location of the tumor and context of work selected by the surgeon (intervention without neuronavigation system). Items n°3 to n°9 represented the main surgical stages required until the detachment of the scalp. A first conflictual item appeared within the detachment of the scalp (item 10). A control of the surgeon's motor skill was required to preserve the sub-temporal muscle inserted under the scalp. Item n°11 concerned access to the lesion that was potentially in conflict with the presence of cerebral arteries to preserve. This situation required a set of regulating controls: a small cortectomie on the cortical surface (Sm), a perceptual exploration to find the lesion in-depth (Sp), and perceptual control of the presence of brain arteries (Sp). Items n°12 and n°13 described potential conflicts during the exeresis, involving respectively decision concerning the range of the excision in comparison with the volume of the tumor, and evaluation of the excision completeness. The choice of the range of excision involved the choice between two instruments (Rule), the use of bipolar forceps (A) and the non-use of microscope (A). The surgeon decided to realise an enlarged exeresis to insure that no tumoral tissues would be forgotten (Sm). Evaluation of the excision was in conflict with the fact that the lesion in depth was difficult to perceive. To control the complete excision in depth, the surgeon proposed to use the microscope (A), and to check the excision (Sp) on the base of the perception of normal brain tissues (Sp). This complete excision also required to respect anterior arteries and their branches (Sp). Item n°14 involved the hemostasis stage that had to cope with the nature of the lesion which was possibly hemorrhagic. This conflict was controlled by a motor skill promoting a careful hemostasis, and knowledge on the relationship between the nature of the lesion and its properties. Item n°15 referred to a conflict potentially appearing during the dura mater closure as regards the state of the dura mater, and requiring a closure as tight as

possible (Sm). Items 16 to 19 corresponded to non-conflictual stages ending the surgical

procedure.

The emergence of surgical conflicts allowed for higlighting the critical stages

envisaged by this neurosurgeon during his planning of this surgical case. These critical stages

were caused by the detection of anatomical obstacles in the surgical procedure (muscles,

arteries, cortical tissue above the tumor), of difficulties to discriminate the tumoral tissues

from healthy tissues, of difficulty to perceive tissues in depth, and of the state of anatomical

tissues (lesion and dura mater). Moreover, we noticed that the two conflicts about amplitude

and completness of the excision, engaged multiple and various controls, involving motor skill

precision, perceptual attention, and alternatives between instruments that will be specified

during the operation, neurophysiological knowledge and choice of instruments. Several levels

of control seemed required to cope with the situation.

Quantitative Analyses

Firstly, we noticed an overall effect of expertise on the number of conflicts (Kruskall-

Wallis test, H=32.2, p<0.001), number of controls (H=33.5, p<0.001), and number of distinct

control levels per conflict (H=18.9, p<0.001). A similar pattern of result was found for verbal

fluency (H=31.7, p<0.001). Pairewise comparisons showed that intermediates were those

reporting the highest number of conflicts and controls and were the most fluent, followed by

experts and residents (table 3). No significant difference was found between intermediates

and experts in the report of control levels per conflict. We noticed that correlations between

complexity and verbal fluency for the two experts and Intermediate 2 narrowly missed

conventional significance levels (for the two experts, Tau-b=0.50, p=0.06; for Intermediate 1,

Tau-b=-0.50, p=0.06). It means a possible confounding effect of verbal fluency with surgical

complexity.

Individual stepwise regression analysis with surgical complexity and verbal fluency as predictors were presented in Table 4. Regression models with surgical complexity as single factor represented respectively 75% and 73% of the variance in number of conflicts reported by the two experts (Expert R: adjusted R^2=0.75, $\boxed{X}$=0.89, t=5.05, p=0.01; Expert 2: adjusted R^2=0.73, $\boxed{X}$=0.88, t=4.80, p=0.02). The number of conflicts significantly increased with surgical complexity for experts (Figure 1). Conflict was added as a predictor for cognitive control and control levels (Table 4). We only noticed a significant decrease in the number of control levels activated with surgical complexity for Intermediate 1 (adjusted R^2=0.46, $\boxed{X}$=-0.72, t=-2.77, p=0.03).

Table 5 shows the proportions of Skill-Rule-Knowledge and Assistance based controls activated by each participant according to the expertise level. The experts activated a higher proportion of knowledge-based control to regulate conflicts (40.2%, CI=38.2%-42.2%), as compared to intermediates (30.3%, CI=28.9%-31.7%) and residents (23.3%, CI=17%-29.6%). The two resident surgeons significantly activated a higher proportion of motor skills to regulate conflicts (41.1%, CI=33.9%-48.3%), than intermediates (27.8%, CI=25.1%-30.5%) and experts (25.3%, CI=21.8%-28.8%). Intra-group comparisons of global cognitive control distribution showed significant differences between Resident 1 and Resident 2 (Chi²=18.4, df=4, p<0.01) and between the two intermediates (Chi²=29.3, df=4, p<0.001) but not for the experts (Chi²=5.6, df=4, p>0.20).

DISCUSSION

The qualitative analysis of one surgical case envisaged by a surgeon showed us that it was possible to extract critical stages among pre-operative planning procedure. Theses critical stages involves conflicts that must be anticipated and elucidated by the surgeons to insure an activity maintained in the boundaries of safety and acceptable performance (Rasmussen, 1997). Various controls were sometimes activated to cope with a surgical conflict. They

referred to sensory-motor and cognitive abilities, but also the well management of assistance, like the relevant use of surgical instruments. These controls correspond to solutions found by the surgeons among the resources of their work system to cope with the situation. Conflicts and controls depend on the specific nature of the surgical case, but also on its complexity and competencies of the surgeon. Quantitative analyses of our study sustained this idea. Whereas intermediates reported the largest number of conflicts, we observed that only the two experts reported more conflicts with surgical complexity. To regulate conflicts, the two experts significantly activated a larger proportion of knowledge-based control, than intermediates and residents, though residents significantly activated a larger proportion of motor-skill based controls than intermediates and experts. With the increase of surgical complexity, we noted that one intermediate reduced the number of levels of control to cope with conflicts.

We must underline that these results must taken with caution because of a set of limitative factors: the sample size, the fact that surgeons come from the same neurosurgical department, the inclusion in the sample of a referent expert who selected and classified the surgical cases. Notwithstanding, the large number of cases allowed us to carry out a quantitative analysis of verbal protocols through individual linear regression models to analyze the variance contribution of various factors. Notably, we controlled the impact of verbal fluency as a confounding predictor on results. Its measurement made it possible to take into account the possible verbal "over-investment" of participants implicitly thinking that the size of their report would be considered as a performance indicator. Moreover, the measure of the referent expert's performance and its comparison with another expert's allows us to highlight the consistency of pre-operative planning activity for experts. Even though the referent expert has more knowledge on clinical cases than the second expert, both were equally sensitive to the increase of potential conflicts with surgical case complexity and privileged knowledge-based control.

This approach of conflict and control confirmed findings obtained through other indicators present in the literature. We found that intermediates were those producing the largest number of conflicts and controls. These results can be explained by the "intermediate effect". Research in the medical domain showed that intermediates elicit considerable amount of information during information recall, diagnosis or decision-making (Patel *et al.*, 2000). The fact that we found no significant correlation between intermediates' conflicts and surgical complexity supports the idea that the "intermediate effect" is effectively based on an irrelevant search for hypotheses (Patel *et al.*, 1994). Only the two experts attuned their situation assessment during planning to the task demands through an increase of conflict detection with surgical complexity (Flin *et al.*, 2007). Moreover and in accordance with Rasmussen (1986), experts privileged knowledge-based control. In our analysis, knowledge-based control of behaviour regulates conflict and as such does not constitute an inert knowledge (Cook & Woods, 1994). Knowledge-based control allows experts to have an in-depth understanding of the conflict content (deep reasoning, Patel *et al.*, 1994), whilst the two residents privilege a straightforward regulation through motor actions to cope with difficulty (shallow reasoning). Finally, the decrease in the number of control levels for one intermediate can be explained as a consequence of an increase in mental workload. But, of course, no conclusion can be reached with a result found only for one surgeon.

In the future, we plan to refine several parameters of our experimental design. We need a more accurate measurement of surgical complexity to pinpoint the conditions in which conflicts arise. The qualitative content of conflict and control must be systematically analyzed to apprehend surgical performance and differences among surgeons. The first qualitative analysis shows that it is possible to track how surgeons are able to detect potential conflict and find resources in their work system resources to cope with them. It represents relevant information to define the modalities of assistance coming from information systems in the

scope of medical education and ergonomics of imagery-guided systems. The definition of

neurosurgical information requirements would also benefit from the comparison of conflict

and control reported both in pre-operative and intra-operative conditions. Frequently,

unanticipated surgical events occur in the operative theatre. Wiegman et al. (2007) showed

that disruptions in surgical flow were correlated with surgical error. An articulation between

observation of disruptions (Healey *et al.,* in press), and report of conflicts could represent an

interesting development in future research.

Acknowledgments

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TABLE 1: Summary of clinical cases classified
according to the increasing order of complexity

N° file	Critical data and location	Histopathology
File N°1	A 48 year-old man, right-handed, 2 generalized seizures, normal clinical examination Right middle frontal gyrus	Cavernoma
File N°2	A 65 year-old man, right-handed, headaches and mild aphasia for one month Left superior frontal gyrus	Glial tumor
File N°3	A 20 year-old man, right-handed, left hemiparesia for 6 weeks, headaches and bradypsychia Right fronto-temporal insular area	Glial tumor
File N°4	A 53 year-old woman, right-handed, weakness in her right lower limb when walking Left fronto temporal insular convexity	Meningioma
File N°5	A 33 year-old woman, right-handed, headaches. Left fronto temporal insular area	Glial tumor
File N°6	A 57 year-old woman, right-handed, trigeminal neuralgia involving the left mandibular and maxillary nerves Left cavernous sinus and tentorial incisura	Meningioma
File N°7	A 16 year old boy, right-handed, headaches, insipid diabetes and bitemporal hemianopsia. Suprasellar area	Craniopharyngioma
File N°8	A 35 year-old woman, right deafness and vestibular syndrome. Right ponto-cerebellar area	Vestibular Schwannoma
File N°9	A 51 year-old woman, headaches and paresthesia in four limbs with pyramidal reflexes and right hypoglossal nerve palsy. Anterior part of the foramen magnum	Meningioma of the foramen magnum

TABLE 2: Conflicts, controls and non-conflictual items coded from folder n°2, Expert 2
(Sm : motor skill; Sp: perceptual skill; R: rule; K: knowledge; A: assistance)

Item	Non-conflict	Conflict :Surgical work system/Work domain	Control of conflict
1	Location of the tumor		
2	Do not use the neuronavigation system		
3	Suggests a slightly enlarged excision		
4	Installation of the patient, type of head board		
5	Incision		
6	Shaving of the scalp		
7	Form and amplitude of the incision		
8	Preparation of the operative field (Betadine, infiltration)		
9	Detachment of the scalp		
10		Detachment of the scalp/ Insertion of sub-temporal muscle	Sm(respect of sub-temporal muscle)
11		Access to the lesion in depth/ Presence of cerebral arteries	Sm(small cortectomie on the surface) Sp(find in-depth lesion) Sp(control of brain arteries)
12		Range of the excision/ Volume of the tumor	R(excision with dissectron or sucker) Sm(enlarged exeresis) A(bipolar forceps) A(non-use of microscope as a first step)
13		Complete excision/ Lesion in depth	A(microscope at end of procedure) Sp(check of complete excision in depth) Sp(recover normal brain as possible) Sp(well respect of previous arteries and branches)
14		Hemostasis/ Possibly hemorrhagic lesion	Sm(careful hemostasis) K(injury possibly bleeding, because possibly infiltrative lesion)
15		Dura mater closing/State of dura mater	Sm(closure dura mater as tight as possible)
16	suspension		
17	Osteosynthesis of component bone and closure		
18	Replacing the bone powder		
19	Closure of the scalp using the usual technique.		

TABLE 3: Conflicts, cognitive controls, number of controls per conflict, number of levels of control per conflict, and number of words activated by each surgeon (n=9 surgical cases per participant)

Participants	Median [Min-Max]			
	Conflict	**Control**	**Level of Control/Conflict**	**Words**
Resident 1	7 [2-16]	13 [3-28]	1.5 [1.1-1.8]	434 [324-519]
Resident 2	3 [1-7]	6 [2-14]	1.3 [1.0-2.0]	128 [96-182]
Total Residents	5.5*	9.5*	1.4*	253*
Intermediate 1	18 [13-40]	58 [23-108]	1.9 [1.4-2.6]	1248 [363-1771]
Intermediate 2	28 [20-34]	65 [55-90]	2.0 [1.6-2.3]	1279 [799-1570]
Total Intermediates	24*	63*	2.0	1248.5*
Expert R	10 [3-21]	30 [6-89]	1.7 [1.0-2.2]	513 [390-1119]
Expert 2	10 [5-27]	28 [14-72]	1.8 [1.5-2.1]	443 [277-667]
Total Experts	10*	29.5*	1.8	490.5*

* z value for Kruskall-Wallis pairewise comparison with p ☒ 05

TABLE 4: Individual multiple regression models for each cognitive variable measured. Step by step evaluation of the models with [X] values of predictor contributions.

| Variables	Participants	R	Adjusted R²	F	P value	Verbal fluency [X]	Complexity [X]	Conflict [X]
Conflict	Resident 1	0.42	-0.10	0.65	0.53			N/A
	Resident 2	0.65	0.24	2.23	0.19			N/A
	Intermediate 1	0.71	0.34	3.04	0.12			N/A
	Intermediate 2	0.77	0.54	10.36	<0.02	0.77*	0.56	N/A
	Expert R	0.89	0.75	25.54	<0.02	0.52	0.89*	N/A
	Expert 2	0.88	0.73	23.05	<0.003	0.28	0.88*	N/A
Control	Resident 1	0.92	0.83	40.42	<0.0001	-0.08	-0.12	0.92*
	Resident 2	0.91	0 .80	33.71	<0.002	0.15	0.27	0.91*
	Intermediate 1	0.89	0.77	27.20	<0.002	-0.02	-0.08	0.89*
	Intermediate 2	0.80	0.42	2.92	0.14			
	Expert R	0.90	0.79	30.94	<0.002	0.90*	0.33	0.37
	Expert 2	0.97	0.94	125.62	<0.0001	0.23	-0.03	0.97*
Control level	Resident 1	0.63	0.03	1.07	0.44			
	Resident 2	0.46	-0.26	0.45	0.73			
	Intermediate 1	0.72	0.46	7.68	<0.03	-0.24	-0.72*	-0.02
	Intermediate 2	0.51	-0.18	0.59	0.65			
	Expert R	0.51	-0.19	0.58	0.65			
	Expert 2	0.70	0.17	1.56	0.31			

* Predictor retained in regression model for its significant contribution: t test with p<0.05

TABLE 5: Global proportions of Skill-Rule-Knowledge and Assistance
based controls activated by each surgeon
n: total number of controls and the highest total percentage
found in bold type

	Knowledge	Rule	Perceptual Skill	Motor Skill	Assistance	n
Resident 1	30.7%	4.3%	14.3%	40.0%	10.7%	121
Resident 2	8.5%	18.6%	18.6%	44.1%	10.2%	59
Total Resident	23.3%	9.4%	15.6%	**41.1%***	10.6%	180
Intermediate 1	28.9%	10.6%	10.2%	29.4%	20.9%	385
Intermediate 2	31.2%	17.3%	14.2%	26.8%	10.5%	641
Total Intermediates	**30.3%**	14.9%	12.7%	27.8%	14.3%	1026
Expert R	43.1%	6.6%	21.7%	21.0%	7.6%	272
Expert 2	37.7%	6.2%	18.7%	29.2%	8.2%	305
Total Expert	**40.2%***	6.4%	20.1%	25.3%	8%	577

- Significant Confidence Interval non-overlap between surgeon groups, p <0.05
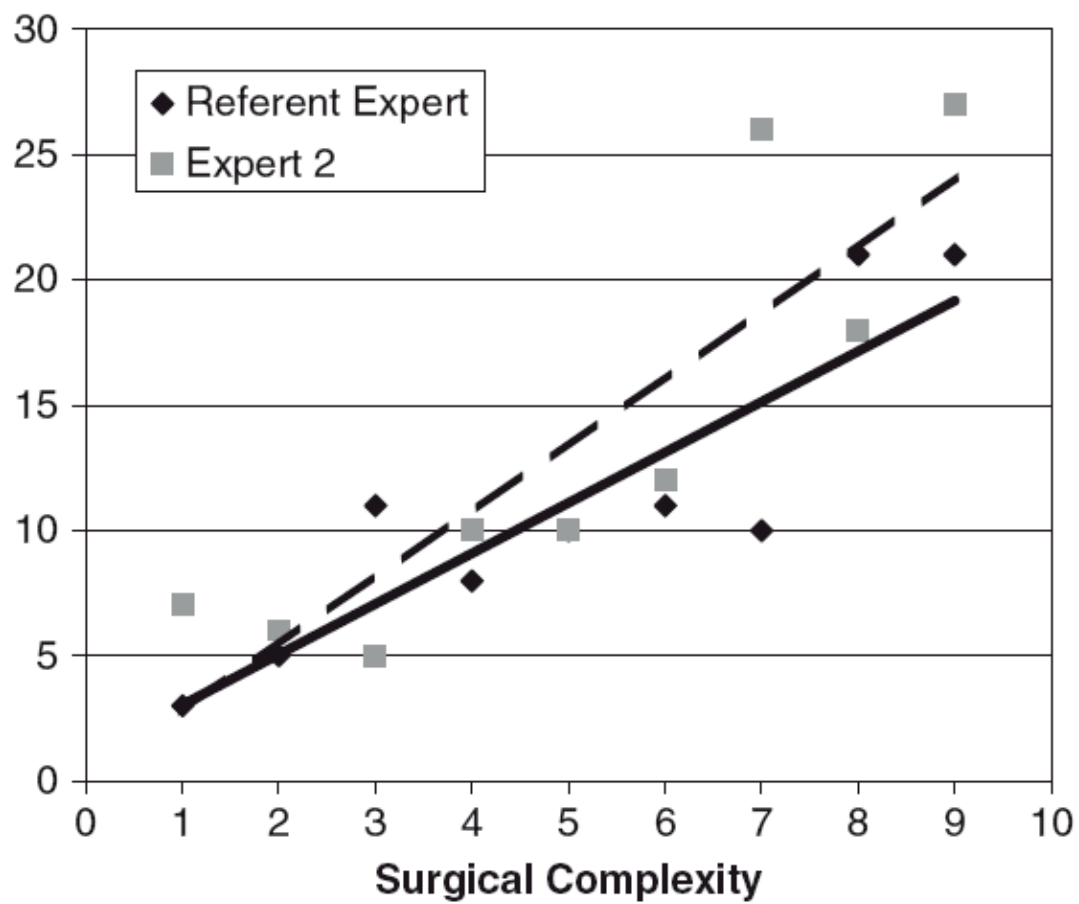
Figure 1. Number of conflicts reported by the two experts along with surgical complexity with linear trends (in dashed line, linear trend for Expert 2).