Behaviors, Strategies, and Subconscious Visualizations of Eskom Grid Controllers Using an Insight Quotient (InQ) Approach

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***Abstract*— Within the South African, Eskom, National Control Centre, highly skilled individuals are responsible for the control of the transmission grid. It is imperative that we understand how these individuals make fast complex decisions when they perform control operations. In order to obtain information about the mental processes, which enable them to make fast intuitive decisions a three-part protocol was used. The first step consisted of video recording the voltage controllers at work on a network simulator. This was followed by in-depth interviews in order to identify their control strategies. Then the subconscious mental imagery, which makes it possible for them to operate, was elicited. In this research expert and novice voltage controllers were included as well as one in-house Human Machine Interface (HMI) developer. The findings were that over and above the conscious control strategies employed the controllers used sophisticated subconscious mental strategies and images that allowed them to simplify the overwhelming quantity of data presented to them in order to effect fast complex operations. The elicitation was achieved by developing the controllers' Insight Quotient or InQ. These findings show great promise when it comes to understanding how controllers perform their complex task.**

Keywords*— *Power System Operations and Planning, Power System Visualization, Human Factors, Mental Models, Naturalistic Decision Making, Insight Quotient, InQ.

I. Introduction

The South African electrical power grid is controlled from the national utility's (Eskom) control room near Johannesburg. The ESKOM National Control Centre (NCC) is a complex environment in which a small number of staff interact with the grid, each other, and other Eskom staff in the field [2]. This is done in order to provide the necessary supervision and central control for the Eskom network, which forms the largest partner in the Southern African Power Pool (SAPP), which includes the Democratic Republic of Congo, Tanzania, Malawi, Zambia, Angola, Namibia, Botswana, Zimbabwe, Mozambique, Swaziland, and Lesotho. As a result the actions of the Eskom controllers have far reaching consequences for the country and the region. Prior to this research very little, was known about what makes these network controllers competent. Within the NCC work on the Voltage control desk demands the most skill, as reactive power and voltage are fast changing variables (unlike active power or frequency) [1]. In order to carry out their duties the controllers need to have access to a variety of technical information, which is presented to them on computer screens [3], via telephones, and in person [4]. However, the presentation of data is not sufficient for the controllers to do their work. The most critical factor is their interpretation of the data to form useful information [6], [7]. Before this information can be used it is processed at an unconscious, then at a subconscious, and finally at a conscious level [9]. The purpose of this research is to elicit [12] and understand the conscious and subconscious mental representations used by the controllers in their interpretation of the network data [23]. In this research we are investigating how knowhow arises in the controllers' awareness, how it is expressed, and how they use it, not how it is acquired [9]. It is important to note that before the subconscious representations were elicited the controllers were not aware of their existence. As a result they had to develop what the author terms "InQ" or Insight Quotient, which is a measure of a person's ability to identify and report on subconscious phenomena [24]. In other words the controllers had to be instructed on how to access the subconscious aspects of their experience while working. This process requires that controllers first become aware of their physiology, in order to indentify which part of their body has been activated, this is particularly significant when they experience strong emotions [21]. Then they are made aware of eye movements, which correspond to their brain accessing imagery appearing in their mental field [25]. Finally they needed training in order to be able to express and describe whatever subconscious representations they become aware of [21], [18], [25]. This initial lack of insight into their subconscious mental representations and their qualia structure [18], [22], in conjunction with conscious control strategies is what this research was seeking to address. This is because, as demonstrated by Libet [19], *these subconscious processes determine behavior when short time frames are involved*! Thus it is they and not conscious forces, which control behavior under such conditions. Understanding such subconscious events is of critical importance in order to improve controller behavior, minimize errors, and assist with the training of novices.

This research is not about knowledge acquisition it's about knowledge manifestation at the level where we can have access to it as qualia (at the subconscious level) [18]. We want to bring subconscious experiences to consciousness where

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they normally remain just outside full awareness, as pointed out by Anderson [10], Damasio [21], Pinker [9], and Swaab [22].

The presence of such experiences is predicated by somatically structured events as a result of extremely complex pattern recognition, reactions of the whole brain, which the controllers call emotions, which they then use to act on the network via the HMIs [21]. The purpose of the research therefore is to identify what arises in awareness, in the brain of experts and novices, as early as possible in the chain of processing (most of which is outside awareness). This is in order to assist the controllers to manage their mental processes by creating self correcting feedback loops as early in the brain computation process [9] as possible (by gaining access to at least the subconscious manifestations) and so help them become more effective in what they need to do. In order to do this a neuroscience perspective was adopted, which is based on the computational model of the brain [9], [21], [22].

In this model the experience of things is processed in layers, from raw sensory excitation along nerve pathways continuously processed [21], up the spinal column to the brain stem, and the limbic system from where it is correlated unconsciously with past experiences in various non mind-mapping brain regions, until it registers as qualia-rich experience [18] at mind-mapping regions subconsciously, finally arriving to full conscious awareness [21]. Also keeping in mind that a lot of our experience is self-constructed rather than arriving from the "outside" because in order to create a complete experience our brain has to fill in many gaps [22]. All these elements are then cross correlated for relevance in what Damasio [21] calls *convergence-divergence zones*, their significance is then identified and appropriate responses determined first unconsciously [21], then subconsciously in mind-mapping brain areas like the prefrontal cortex, the motor cortex etc., until the illusion of conscious deliberate action takes place as per Libet's findings [19], supported by confabulations after the event [22]. This is reportedly what happens during error investigations, where controllers tell the "story" of what happened rather then report *on* what happened. As a result there is nothing to be done but wait for the next error. From the findings of this research it will be shown that an alternative is now possible. That is that once the controllers become conscious of what their brains are presenting they can intervene in time, as well as become sensitized to the differences between (paying attention to) mental representations and information on the HMIs.

NCC management had indicated that they wanted to improve standards of performance, minimize errors, facilitate training of new controllers, improve adaptability to new HMIs, and get constructive feedback about new HMI design. This research was only conducted on the voltage desk staff as they operate under the shortest time frames.

The research questions asked were:

- **How do controllers of various capabilities work on the grid simulator?**
- **What are the control strategies used by controllers with varied working experience?**
- **What are the subconscious representations in the mind of each controller, which underpin their control decisions and behavior on the grid simulator?**

Please note that the Neuro-linguistic Programming (NLP) elicitation methods and questions used for this research have been discussed in a previous paper by the author [25].

II. Methodology

According to Nielsen [20] the total number of seven plus one participants interviewed was deemed sufficient to obtain reliable results. Of the seven controllers selected at the NCC two are experienced and skilled Senior Advisors (SA), two are Experienced Voltage Controllers (EVC) and two are New Voltage Controllers (NVC). The seventh is a New Female Controller (NFC) that had undergone training, but had not yet been authorized to work on the voltage desk. She was included to examine differences in perspective, as she was really new to the environment as well as any other possible gender related differences. At the time of the research there were no female controllers working on the voltage desk, she was only authorized to work on the Loading (Frequency control) and Transmission (Operations and switching) desks.

An eighth person was included in the interview list. He is responsible for Man Machine Interface design but does not do shift-work or work in the control room itself. He was included in order to highlight any differences between control room staff and interface designers. This is very important in the NCC because often the designer finds himself at odds with the controllers regarding HMI design.

Each controller was given the same task to perform on the ESKOM grid simulator. This task consisted of a single 400 kV line trip, followed by a second 400 kV line trip within a few seconds, in the same area. This double contingency would normally result in a voltage collapse in the area. The controllers' were video recorded working on the grid simulator. During which time they made brief comments about what they were doing as per Verbal Protocol Analysis (VPA) requirements [23]. The video recording was then played back to them and they commented further on their activities (Retrospective VPA) [23].

A series of questions [25], [12], [13], [14], were asked to elicit the underlying mental representations that made their decisions possible and reveal the structure and content of their subconscious representations.

The video recordings of their performance on the simulator as well as the video recordings of the interviews were analyzed to extract the material that represents the findings of this research.

The findings from the interviews were summarized and the relevant controller strategies and visualizations were compiled.

III. Findings from the Interviews

A. How They Worked on the Simulator

The equipment used in the simulator included two monitors, two keyboards (one for performing switching operations and the other for selecting displays on the monitors), and a mouse.

It was observed that **the two SAs** used both hands, one on the mouse and the other on the switching keyboard, to perform control functions (of the two, one is left handed). They remained relaxed and appeared confident sitting back in their chair. They used small hand and wrist movements in their work. They seemed to maintain an overview of their environment, working fast and anticipating contingencies. The distance between their head and the monitors was maintained at over one meter.

The two EVCs also seemed calm. Their movements were slower; they both sat forward on their chair and seemed to peer into the monitors more fixedly (this may have cognitive implications of not considering the big picture as well as having a reactive rather than proactive attitude with an external locus of control). Of the two only one used both hands to work. They both leaned on their elbows and supported their chin with their left hand when not using it. Their hand movements were large and thus took longer. Their head to monitor distance was about 0.8 m. One of them was quite sensitive to the volume of the audible alarms. **The two NVCs** used only their right hands to work both the mouse and keyboard. Their left hands were not used at all. They appeared stiffer and more abrupt in their movements, focusing on the monitors (peering into them with similar possible cognitive consequences as the two EVCs). Their movements were big, fast, and abrupt. They seemed to experience and display strong emotions. Their head to monitor distance was about 1m to 0.8 m for the one and 0.8 m for the other.

The NFC was similar to the NVCs but was even more drawn in by the monitors, progressively moving her head closer. As the simulated contingency unfolded she seemed very worried. Her movements were big (both body and right arm). Her left hand was folded behind her back and not used at all. Her head to monitor distance varied from 0.7m to about 0.5m. She appeared sensitive to the level of audible alarms.

The MMID works in an office in front of a single monitor the same size as that of the controllers' (they use two at a time), however the distance between his face and the monitor is about 0.4m. His ability to see the information displayed is thus better than the controllers who work from about 0.7m to over 1m away from the monitors. His work does not involve interacting with a dynamic network. Instead he is responsible for finding practical ways of converting data into information and implementing new technologies.

B. Control Strategies

In this section the control strategies, i.e. what the participants looked for and in what order, are listed. This was done by creating a matrix having a row for each of the fifty-nine statements derived from the comments made by the participants during their interviews. Each of the eight participants was associated with a column in the matrix. Crosses were inserted where a comment came from a particular participant. What follows is a summary of the information that emerged from the matrix. Comments that pertained to all concerned were omitted in this paper due to space constraints. They are however included in the MSc dissertation upon which this paper is based.

The following summarizes the information that was derived from the comments made by the two SAs and the two EVCs.

They have self-created, predetermined voltage range limits per region of the network. They use these in order to be **proactive** in their control strategies. In particular they have high voltage preset levels for high loads, or mental templates with high and low values that are used for scanning. **They use simple mental block diagrams to isolate and focus their attention on an area on which they work.** After they were made aware of this phenomenon during the interviews, they referred to this mental visualization technique as "*rubber banding*", i.e. putting a mental rubber band around the contingency area. This makes it stand out while the rest of the network disappears in their mind. This **"rubber banding"** is the most significant strategy step difference between the experienced and the inexperienced group. The experienced group enquires into the causes of faults when they occur. They have become accustomed to displays that are difficult for novices to interpret. They also have high stress thresholds.

The following information summary came from the SAs' list of comments.

They "step back" regularly to see the big picture; they use varied **proactive** strategies to control the network; they are mindful of external conditions (time of day etc.); they mentally exclude useless information, and experience a range of normal, abnormal and critical emotional states, as per network conditions. They have control strategies, which include mental pictures that "show" them what to do. These get progressively simpler as contingencies get more severe! They check their decisions with the shift manager if there is time. Sometimes they may work too fast.

The following information summary came from the EVC s' list of comments.

They have a structured sequential approach to their work relying on their memory of what has happened before or instructions from the shift manager. They are aware of the consequences of their actions on plant (e.g. load shedding). They do not experience or express intense emotional states (some say they are "too calm"). Serious contingencies cause them to feel sharpened alertness.

THE FOLLOWING INFORMATION SUMMARY CAME FROM THE NVCS' LIST OF COMMENTS.

In general, their mental model works against them. They create exaggerated emotions by imagining situations that are worse than reality, leading to feelings of panic (shaking, hot anxiety in the gut and confusion in the head; these limit information processing abilities), momentary blank-outs and loss of control. They need senior personnel around them to feel secure and calm under extreme contingencies. They use elaborate detailed or scenic mental images and do not "zoom out" to see the big picture. They always check with the shift manager before operating, especially under contingency conditions.

THE FOLLOWING INFORMATION SUMMARY CAME FROM THE NFC'S LIST OF COMMENTS.

The NFC's work on the Loading Desk is not as urgent as that of the voltage controllers; her work has to be pre-approved. On the simulator she thought in terms of what was presented on the monitors and did not use mental models to the same extent as the VCs. She experiences low stress and reports high satisfaction in her normal work.

THE FOLLOWING INFORMATION SUMMARY CAME FROM THE MMID'S LIST OF COMMENTS.

The MMID also works in a low stress environment and reports high satisfaction from his work. He effortlessly creates complete, elaborate and varied mental images and is aware of them (unlike the others). His strategies are intended to convert data to information, by prioritizing, categorizing, and depicting only relevant information on the monitors (particularly alarms). He is looking to the future (five to ten years ahead) where computer networks instead of simple SCADA systems and "intelligent" information processing will be the norm. He is constrained by the fact that he is future orientated and has to "drag everyone along", as controllers tend to be reluctant to embrace changes.

C. Subconscious Mental Representations

This section underpins the previous two as the arising of subconscious mental representations determines the decisions and actions taken by the controllers. Of particular interest were the visual aspects of their mental representations. It is also very important to note that none of the controllers were consciously aware of the arising of mental imagery before this study. It is important to keep in mind that for everything listed below there are brain structures at work. To the extent that these brain structures are responsible for excessive emotions to that extent higher brain functions suffer.

SA1: He holds in his mind a page with voltage values that he uses as a template against which he compares the actual voltage display page. When there are discrepancies he feels pressure in his chest, this prompts him to act and make corrections.

For analysis work he has the whole network in front of him (mentally). First as a ball (+/- 20 cm in diameter), then opens it out flat, in full color, at arms length (to the size of +/- 4 m^2). He only looks at one Region / Area / Station at a time, as the whole is too big for him to "see" all at once.

Under contingency conditions, he visualizes the substations in the affected areas as 2D unlabeled blocks with lines in between them representing the power lines. The mental images consist of +/- 6 parts (two or three blocks with lines in between). They are white on a grey background. He uses these simple mental images in order to decide what to do next as well as to determine the consequences of his actions.

SA2: He has a small mental template with +/- 5% voltage values in it (a small mental block) that he runs against the voltage page values displayed on the monitor. From performing such a scan he gets either a normal, abnormal (close to 5%) or urgent feeling (over 5% difference). He has divided the voltage display page into quadrants.

When there is a fault, he mentally sees the substations in the area involved as simple blocks with just a few power lines linking them and no labels (+/- 6 part image). The presence of a flashing red block in this mental picture tells him that there is trouble. He then uses operating steps that he visualizes on mental "cards". These "cards" are white (normal condition), yellow / orange (abnormal) and flashing orange (urgent). The amount of information (procedural steps to correct problems) on them gets less and less as they go from normal to urgent. He has a proactive approach and mentally discards useless information. He crosschecks his decisions with the shift manager to get perspective (big picture) when there is time.

For network analysis under non-urgent conditions he uses 3D simple mental pictures in color.

EVC1: He watches the voltage page on the computer monitor and if there is a color change in one of the numerical voltage values or an audible alarm he knows that here is a contingency. He then asks the other members of the shift for its cause. He also has simplified one-line mental diagrams of main substations that help him to work out how to operate.

He works from memory of past similar events when deciding what to do, or otherwise requests instructions from a senior person.

He uses a simple mental image to visualize the contingency area and to decide what to do. This is a block with lines (+/- 3 part image). This mental diagram gets sharper with more contrast when there is trouble, this helps to focus his attention and increase the speed of his response.

EVC2: He scans the monitor voltage display page using key points and decides what needs attention (proactive).

In contingencies he sees a "blob" representing the area with just the main lines shown (+/- 3 part image). This switches on like a light in his mind while he works and disappears when the emergency is over. When things return to normal he mentally sees closed breakers and MW values added to his diagram.

NVC1: During the double contingency he saw red alarms flashing in his mind (more than the actual number) and got an 'out of control' feeling.

Mental images, of what the substations look like physically, started to fly past in his mind, in a blur, and he had difficulty finding use for these pictures. He said that he was looking for a picture that would tell him what to do and when he did not find it he couldn't decide what to do. This led him to feel anxiety, confusion, and unconscious actions. He said that he then needs someone senior around him, for support, in order to think clearly.

NVC2: He has **detailed** elaborate mental pictures for each region under normal conditions and operating strategies.

During the double contingency he got fixated on a capacitor bank and could not mentally zoom out, to see the big picture and thus know where to go next.

He is proud of his ability to have a very comprehensive image of the network in his mind but does not yet know how to navigate that image under stress. This leads him to panic and freeze.

NFC: She thinks in terms of what she sees in front of her on the monitors. Her work does not require fast analysis like the voltage control staff. When she saw the lines trip she thought that the voltage control person would have problems and felt alert. She requires confirmation of her operations by a senior person.

MMID: His mental images are sparse, clean, limited in variety, with color coordination and visually aesthetic.

His criteria for good images are: Color quality, and neatness. He can, at will, create 3D, complex images (comprising of +/- 9 parts) and metaphors that he can manipulate in mental space with ease. His visual mental capacity is very advanced.

IV. Conclusions

Firstly the way the controllers work on the simulator desk is very revealing in terms of what is going on in their brain. The two SAs took positions further back from the monitors that all the others, this could imply that their decisions with respect to the contingencies were less determined by what they saw in the external environment, the HMIs etc. This is supported by the information they provided about the mental imagery in their mind, which was the primary factor in determining their actions. This mental imagery was more significant than in all the other controllers and allowed them to achieve the best results as far as saving the network goes. That in itself is a training strategy worth implementing for everyone. This would involve all controllers being conditioned to first step back to view the problem in their mind, and then act on the HMIs.

Further, it appears that the experienced controllers work by simplifying the information that they get from the monitors by "*rubber banding*" (mentally isolating) the affected area and representing its key elements with about five to six parts of mental visual information. This allows them to deal with variety, complexity, and new events on the dynamic network by mentally focusing on the essentials. This is necessary as the information presented on the monitors (under contingencies) is far too much to absorb at once (in some large scale contingencies there could be as many as 2000 alarms active). These simplified mental diagrams assist them in knowing what to do next and what will be the consequences of their actions within the affected area, as well as the areas around it. The best among them do all of this proactively, by drawing on memory and by visualizing new scenarios. This would be another key strategy. They often make decisions based on what "feels right" as there is very little time for analysis during contingencies. These results are supported by the work of Klein, Zsambok and others [15], [16]. It also seems that the new controllers are not aware of these "internal" cognitive steps, particularly the ability to zoom out mentally, that can assist them to get direction from seeing the big picture [15], [16]. On the surface the HMI designer's strategies are in keeping with the controllers' requirements. However his images (also neat and simple) do not match the ones that they use. To that extent the controllers are not keen to accept the images devised by the HMI designer, because they don't fit in with what they have "programmed" in their minds [26]. This may be part of what creates the perception that controllers are opposed to new things and change. The controllers say that changes "feel wrong" (the technical term is Cognitive Dissonance) and that they take time to get used to them [26]. They experience this as stress, because of the potential consequences that may follow in the transition period, for which they will be held responsible.

From all the above the three research questions were answered, under each of the three sections listed under Findings. The hidden competencies that are the very foundation of expertise in the control room have, until now, remained vague and invisible. This served to perpetuate the perception, in some minds, that the controllers' job is of a lower grade than that of system engineers. This view is incorrect. Their unique skill lies in being able to integrate the state of the whole network over long periods of calm suddenly followed by contingencies, which are rare. This means that controllers have to jump into action from a state of waiting (perhaps for months) to deal with these contingencies. Contingencies demand instant responses, which may have grave consequences. Finally, it should be noted that the information presented in the findings section is just a layer of representation within the minds of the participants. A much more detailed description of the sub-modality sequences [11-13], as they were activated for each participant, are available, but can not be included here due to space constraints.. The term sub-modality refers to the sensorial components that make up internal representations, i.e. contrast and focus, are visual sub-modalities, tone and tempo, are auditory etc. Behind these sequences are the brain operation layers at a level that cannot be accessed at present, except with the aid of powerful technology (EEG, fMRI etc.) that maps brain activity as it occurs. However it is critical that we keep in mind that for every representation listed above there are brain regions at work, which determine what each controller experiences.

V. FUTURE RESEARCH

An important issue revealed in the investigation, was that of the emotional states and relationships between the various members of a shift play a major role in the control room environment. This is so because constructive emotional states enable higher brain functions whereas destructive ones inhibit it [9]. These aspects of control room life will form the theme of another paper.

Another important issue is that it is incorrect to speak in terms of "controllers" as if they stand apart from the network and control it. This is far from the truth, as the experienced controllers identify with the network as part of themselves (this forms part of their expertise). It is far closer to the truth, to state that the network, the HMI, the individual controller, every other member of a shift, NCC management, and any other factors that impact on them all form a system [17]. This system has parts, which affect each other with varying time constants and multiple layers of physical, mental, emotional, and technical interactions. This systemic view warrants further research as we move towards more complex scenarios and larger networks [17]. This research therefore is only a first step in realizing the greater whole.

It is the author's opinion that the above should be considered, if not before, at least together with HMI designs from vendors that present their systems for controllers to "fit into". HMI systems can then be engineered for greater integration. The same applies to training interventions where the processing mental structure as well as the technical information should be considered for transfer to the student.

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