Chapter 3

Recall Performance in Air Traffic Controllers Across the 24-hr Day: Influence of Alertness and Task Demands on Recall Strategies

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Additional information is available at the end of the chapter

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1. Introduction

Air traffic controllers' (ATCs') work evolves constantly, concerning in particular route complexity and traffic density, but also development of supporting technology. Introducing more automation to allow more efficient ATC control and increased safety and security also requires enhanced supervisory activity, situation awareness, processing of larger amounts of data. These cognitive processes place a heavy load on ATCs' memory functions as they require item processing and recall, which are also involved in control operations such as monitoring traffic, controlling aircraft movements, managing air traffic sequences, resolving conflicts. Better understanding of memory processes and of their limitations in expert ATCs may thus be crucial for the development of future automation tools, but also for training and selection of controllers. The aim of the present contribution is to give a comprehensive overview of memorisation performance in air traffic controllers, in light of the most recent memory models. More especially, a series of experiments reveal that ATCs' memorisation performance varies in a complex manner according to both task-related factors (presentation modality, number of items, recall protocol), and task-independent factors. The latter are related more especially to shift-scheduling (time-of-day, on-shift time) and physiological capacities (alertness, automatic item processing).

2. ATCs' performance variations according to task-related factors

2.1. Information processing during control operations

En route ATC involves the processing of information relative to a variable number of aircrafts coming from different directions, at diverse speed and altitudes, and heading to various destinations or that are, on contrary, grouped in a more restricted space, thus requiring more in-depth processing in order to anticipate air-plane conflicts. Presentation modality is of interest as information about an aircraft is presented visually on a strip or script 10 to 15 min before its real-time presentation in the visual modality (radar information) or in the auditory modality (radio information). Radar information includes instantaneous level, attitude (stable, climbing, descending) and speed group, and strips present many information as aircraft call sign, aircraft type and associated speed (or power), provenance and destination, route case (estimated hours of flying), and three cases completed by ATCs with information concerning coordination information with other ATCs, or changes requested in flight.

A number of simulation studies and *in situ* ATC observations explored the way such factors may impact on memory performance. Thus, expert ATCs show high recall performance of aircrafts and their position on a sector map, and poorer recollection of details regarding an aircraft (Means et al., 1988). Higher recognition accuracy for aircrafts involved in an impending conflict compared to those that would not cross or cross in some near future confirmed the impact of aircraft status on memory performance (Gronlund et al., 1998, 2005). Simulation studies revealed higher recall when navigational messages were presented in the auditory rather than in the visual modality. In addition, performance dropped considerably when message length increased beyond three commands, while command wordiness (2 or 4 words) had only limited effects on recall (Wickens & Hollands, 2000; Barshi & Healy, 2002; Schneider et al., 2004).

2.2. Information processing according to presentation modality: The auditory superiority effect

Controlled laboratory studies have systematically explored task-related factors that may affect mnemonic performance and have led to the proposal of integrated theoretical models. More especially, encoding and processing of auditory compared to visual verbal material has systematically revealed superior recall of heard material in short-term memory (for a review, Penney, 1989). A common test in this research field contrasts silent reading and reading aloud of unrelated lists of words, nonwords, letters, or digits (see, e.g., Conrad & Hull, 1968; Frankish, 1985). It is assumed that both silent reading and reading aloud provide phonological information and that only reading aloud provides acoustic–sensory information. This effect was found for the recency part of the serial position curve in immediate free recall and in serial recall. Overt vocalization of a visually presented list by the subject produced much the same effect as did auditory presentation on the recency part of the serial position curve, but subject vocalization tended to reduce recall in the non recency part of the serial position curve. The modality effect has been observed with both written and oral recall, but seems to be slightly more marked in the former case. This auditory superiority effect, known as the modality effect, was accounted for by modality-related processing differences at different stages of the memorisation process, rather than by strategic differences.

2.2.1. Differences during processing of auditory and visually presented material

Several authors suggested that a long-lasting sensory acoustic trace would be generated for auditory presented words but not for visually presented words (Cowan, 1984; Crowder & Morton, 1969; Crowder et al., 2004; Penney, 1989). The term acoustic–sensory information refers to sensory representations of sounds. Though there is some evidence of a sensory visual trace for seen words, it would be very short-lived compared to the long-lasting sensory acoustic trace that would favour more efficient encoding of heard material. In addition, orally presented list-items would be associated with temporal cues that would not be generated by successively presented visual words. These temporal cues would then result in stronger memory traces and ensure higher recall for heard items (Frankish, 1985, 2008).

Other authors argued that the differences between the visual and the auditory information processing streams would occur when the sensory trace is processed into a short term memory trace. The working memory model (Baddeley & Hitch, 1974) includes a dedicated phonological subsystem, in which the code used to represent verbal items broadly corresponds to the phonetic level. Hence, auditory information would benefit from automatic phonological coding while visual information would require effortful phonological recoding (Baddeley, 1986, 2000; Penney, 1989). Phonological coding would favour mental rehearsal and maintenance of information in a short-term store (Baddeley, 1986), what would result in a larger number of phonologically coded memory traces in a short-term store following hearing than following seeing item-lists. According to Penney (1989) the auditory superiority would be based on the combination of a longer-lasting sensory acoustic trace and automatic phonological coding of orally presented materiel.

2.2.2. Differences during restitution of heard and seen item lists

Differences during item recall were also proposed to account for better immediate recall of heard than of seen materiel. This research is based in particular on the robust finding that when participants recall a sequence of spoken digits the last one is almost always correctly recalled, but if the same sequence is presented visually, recall of the final item is relatively poor. According to Crowder and Morton (1969), this auditory recency effect indicates that an acoustically coded representation of the final list item is maintained in a sensory store, while representations of earlier items are overwritten by successively incoming speech sounds.

Alternatively, Cowan and co-workers accounted for the recency effect by suggesting greater resistance to output interference for heard compared to seen verbal material (Cowan et al., 2002; Harveay & Beaman, 2007; Madigan, 1971). Output interference is defined as the degradation of memory representations as recall proceeds across output positions. Evidence in favour of a greater resistance to interference for heard items came from studies reporting a marked auditory superiority when restitution was based on a free recall procedure (without providing any cues) and a reduced effect when a recognition procedure was used (list items are presented together with new items). Item recognition may be explained by an impression of familiarity for the list-items and would thus not require in-depth processing.

In contrast, free recall requires subjects to explicitly recall each item, thereby degrading the remaining memory traces (Brébion et al., 2005).

Lower output interference has also been proposed to account for the auditory advantage of sentence recall (Rummer & Schweppe, 2005). In line with this hypothesis, Beaman and Morton (2000) showed that following presentation of 16-item lists, subjects preferentially recalled 2-, 3- and 4-item sub-sequences (of the form 15-16, 14-15-16, 13-14-15-16) from the end of the lists. However, while end sub-sequences were recalled with a similar frequency in both modalities on the opening run of a trial, they were recalled significantly more often for heard than for seen items during the course of a trial.

2.3. Auditory superiority for heard versus seen item-lists in ATCs

In light of these findings we explored whether output interference while recalling seen items may be reduced in participants well-practiced in processing visual information, i.e. ATCs habitually processing visual information on a radar. In addition we tested to what extent the effect may be explained by memory load, typically explored by presenting a list of items of variable length. Previous research with this kind of procedure has shown that the amount of proactive interference is much less for smaller set sizes (Oberauer & Vockenberg, 2009) although there can be some proactive interference even at small set sizes (Carroll et al., 2010). We used the procedure described by Beaman and Morton (2000) to explore free recall of heard versus seen 6- and 9-item lists in 15 volunteer ATCs of an en-route centre in southern France. Participants were aged 31.3 years (range: 27 to 42 years old) and had been working for 7 years and 4 months (range: 3 to18 years) in the control centre. The sub-sequences recalled by ATCs at initial and non-initial output positions are summarized in table 1. Analyses revealed significant higher mean numbers of items recalled following hearing (4.9 and 3.6 respectively for 6- and 9- item lists) than seeing the lists (4.2 and 3.2 respectively).

	Visual	Auditory
Terminal item sequences	6-word lists	
6	13	7
5, 6	13	17
4, 5, 6	12	12
3, 4, 5, 6	3	2
2, 3, 4, 5, 6	7	2
1, 2, 3, 4, 5, 6	10	27
Terminal item sequences	9-word lists	
9	24	20
8, 9	22	18
7, 8, 9	7	14
6, 7, 8, 9	3	4
5, 6, 7, 8, 9	0	3
4, 5, 6, 7, 8, 9	1	1

	Visual	Auditory
Terminal item sequences	6-word lists	
5, 6	16	34
4, 5, 6	3	13
3, 4, 5, 6	1	2
Terminal item sequences	9-word lists	
8, 9	14	30
7, 8, 9	1	4
6, 7, 8, 9	1	2

Table 1. Number of each of the terminal item sequences as the opening run (upper panel) and in non-initial response positions (lower panel) during free recall of 6- and 9-word lists with auditory and visual presentation (Galy et al., 2010).

As shown in table 1, ATCs recalled complete 6-item lists three times more frequently following auditory (27) than following visual list (10) presentation, while recall of five-item sub-sequences (2-3-4-5-6) was rare in both modalities (2 vs. 7 respectively). These results further indicate that occurrences for heard lists were tenfold more frequent for complete six-item lists than for five-item sub-sequences, while no such difference occurred for seen lists. Occurrences of equivalent end sub-sequences of 9-item lists (5-6-7-8-9; 4-5-6-7-8-9) ranged between zero and three in both modalities. The auditory recall advantage of these lists appeared to result from higher occurrences of ordered 2- and 3-item end sub-sequences in *other than initial recall positions*.

Taken together, the findings show that ATCs would spontaneously adopt the output strategy consisting of uttering end sub-sequences more frequently for heard than for seen items, leading to, or contributing to significant higher overall performance. They thus further stress the proposal that "auditory presentation seems to protect the end of the list from output interference" (Cowan et al., 2002, p.168). In favour of this hypothesis, these authors showed that the auditory advantage is even more pronounced when output interference is high. Alternatively it has been proposed that the auditory advantage that extends over the last few serial positions is retrieved independently for each item from an echoic trace (Frankish, 2008). According to this author, pronounced recency in immediate serial recall is limited to stimuli that engage the perceptual mechanism involved in linguistic decoding of speech. Further research intended to disentangle different sources of sensory information at input. Thus, Rummer and Schweppe (2005) observed a modality effect for spoken sentences compared to conditions without acoustic–sensory information, i.e., both silent reading and mouthing. As the latter two conditions did not differ from each other, the results would rule out articulatory information at input as a source of the modality effect. Differences due to output modality were also investigated. For written recall the auditory advantage was larger with high than with low output interference, while this difference was not maintained for spoken recall (Harvey & Beaman, 2007). Taken together, the data suggest that both superior auditory encoding and reduced output interference would contribute to the auditory modality effect.

As ATCs are well-practiced in processing successively presented visual information, on contrary to participants in the above-cited laboratory experiments, the present findings favour the idea that differential physiological features may characterize the visual and auditory information processing streams (Penney, 1989). The modality effect may then be implemented in the current models of spoken and of written words, which are divided on the relation between the different levels of processing, which will not be discussed in this issue. Briefly, in some models the transmission of information through successive levels of representation is represented as a unidirectional flow within a feed forward network. Perceptual analysis begins with encoding of acoustic features, which are then translated into phonetic and then lexical representations. In contrast, interactive activation models propose that communication between these levels is bidirectional. Whenever a lexical unit becomes active, feedback connections boost activation of the units that represent its constituent phonemes (for a review, Frankish, 2008).

3. Shift-scheduling and ATCs' functional state

Like in other safety-related job situations, ATC requires operators to work successive shifts; i.e. different teams work in succession to cover the whole 24h-day. As a consequence, controllers are subjected to the negative impact of shift work on biological rhythms, sleep, job performance, and psychological measures (Costa, 1999; Della Rocco & Nesthus, 2005; Dinges et al., 1997; Folkard & Tucker, 2003).

3.1. Regulation mechanisms of circadian variations

It is now largely accepted that the negative effects of shift work result from a disruption of the habitual circadian regulation of physiological and psychological measures (Costa, 2003; Siegrist, 2010). Circadian variations across the 24h-day are under control of two endogenous systems, the homeostatic system expressed by the fatigue accumulating since awakening, and the circadian system evidenced by a sinusoidal variation across the 24h period. Hence, shift work is systematically associated with a cumulative sleep deficit (homeostatic system), and a decreased amplitude of sinusoidal variations (circadian system), thereby interfering with the two powerful factors limiting human ability and, as a consequence, safety and security (Akerstedt, 1991; Akerstedt et al., 2004; Dinges et al., 1997; Folkard & Akerstedt, 1992; Tucker et al., 2006). As stated by Akerstedt (2007, p. 209) "Being exposed to the circadian low (during work/activity), extended time awake or reduced duration of sleep will impair performance".

3.2. Circadian and non circadian variations of subjective and physiological measures in shift-workers

In order to investigate a person's functional state, behavioural, physiological or subjective measures have been used. It is generally accepted that these measures are subjected to a circadian rhythmicity. Shift work effects have mostly been documented by reporting decreased self-rated alertness (Akerstedt & Gillberg, 1990; Galy et al., 2008) and increased occurrences of incidents on the night shift when the circadian decline in human capabilities is further aggravated by a chronic sleep deficit and fatigue (Costa, 2003; Folkard & Akersted, 2003). Laboratory studies have established that alertness is low in the morning, increases during the day until the late afternoon, before decreasing in the evening and reach a minimal level on early morning hours. The shift work literature revealed that in real-job situations alertness also varies with time of day and that the typical diurnal trend would only be marginally modified by shift work scheduling features. However, early morning shifts, extended shift duration and repeated night shifts have been shown to be associated with increased sleepiness, more especially during the last half of extended shifts, particularly on night shifts (Kecklund et al., 1997; Rosa, 1995), but also on day shifts (Tucker et al., 1998).

Circadian variations appear to be less consistent for other psychological measures recorded in several shift work studies, and in particular for self-reported tension (Folkard, 1990; Kecklund et al., 1997; Monk et al., 1985; Owens et al., 2000 ; Prizmic et al., 1995). While some studies reported a circadian trend for perceived tension, others did not, and still others reported an atypical trend. More especially, operators supervising a satellite across 24h-day displayed significant increased self-rated tension and heart rate on the first hour of each shift, even on the night-shift, despite a lower baseline level for heart rate during the night (Cariou et al., 2008). In contrast, when the same satellite controllers rated Thayer’s (1989) Activation-Deactivation checklist, their alertness level was highly correlated with their body temperature (Fig. 1), largely considered as an index of subjects’ functional state. Both measures followed a typical circadian trend, indicating a strong dependency of these measures on the endogenous regulation systems.

Taken together with the shift-work literature, these results indicate that some subjective and objective measures (here alertness and body temperature) show a strong dependency on the endogenous regulation systems, as they display a circadian trend in different shift-work conditions, like in controlled laboratory conditions, despite minor variations in this trend by external factors. This then implies that working during the circadian trough requires an additional effort as operators’ functional state is at its lowest level. Most interestingly, other measures (here subjective tension and heart rate), which are known to display a circadian trend in controlled laboratory conditions, are much more influenced by external factors, so that the trends may vary considerably between situations (or job-situations). Andorre and Queinnec (1998) reported a significant increase on the first shift-hour for real-job performance (pages checked on a computer-screen) in operators controlling a chemical production process. In both studies the atypical trend was interpreted as indicating enhanced cognitive demands following shift take-over in job-situations concerned with supervisory control of a dynamic process. Thus, in shift-work conditions, some psychological and physiological measures, and in particular those that are and other stress-sensitive, would be largely influenced by environmental factors, including meal-timing, task demands, time-pressure and so on, which may mask the otherwise circadian trend of these measures (Averty et al., 2004; Brookings et al., 1996; Khaleque, 1984; Rose et al., 1982).

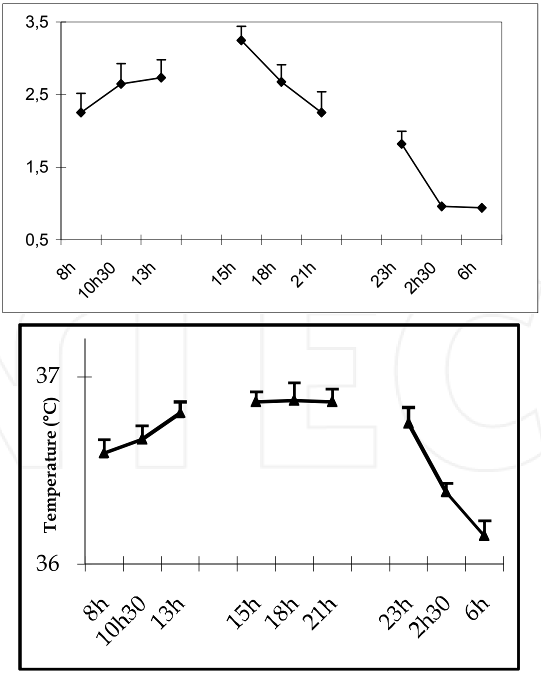

Figure 1. Upper panel: Mean (+/-S.E.) alertness level on 3 occasions within each of three shifts (1h following shift-start, middle, and 1h before shift-end). Lower panel: Mean (+/-S.E.) sublingual temperature on the same recordings (Cariou et al., 2008).

3.3. Circadian variations of subjective measures in ATCs

In light of the inconsistencies of the findings in the literature concerning other subjective measures than alertness, we investigated whether ATCs displayed typical circadian trends for subjective measures and whether on-shift time would modulate these measures. In this job-situation, traffic density variations across the 24h-day determine, partly at least, shift schedules that include in particular overlapping shifts and variable shift-duration.

	Time of recording			
Shift	01:00	07:00	13:00	19:00
06:30 -14:00		0h30	6h30	
07:00 - 17:30		0h00	6h00	
09:00 - 20:00			4h00	10h00
11:00 - 20:00			2h00	8h00
15:30 - 23:00				3h30
20:00 - 07:00	5h00			

Table 2. Time on duty of controllers on each of six shifts at the time each recording was performed (Mélan et al., 2007).

Therefore, 15 volunteer ATCs were asked to rate Thayer's (1989) checklist on 01:00, 07:00, 13:00, 19:00 by indicating whether they were on shift for four hours at most or for six hours at least (table 2). Statistical analyses revealed significant time-of-day and time-on-duty effects for both measures. ATCs rated alertness at a lower level at 01:00 and 07:00 than at 13:00 and 19:00 and tension at 07:00 compared to 01:00, 13:00 and 19:00. However, while self-rated tension was higher following long on-shift time, the opposite pattern was observed for self-rated alertness. In other words, when controllers started day-duty they experienced high alertness and low tension, whereas they reported decreased alertness and higher subjective tension after several hours on duty.

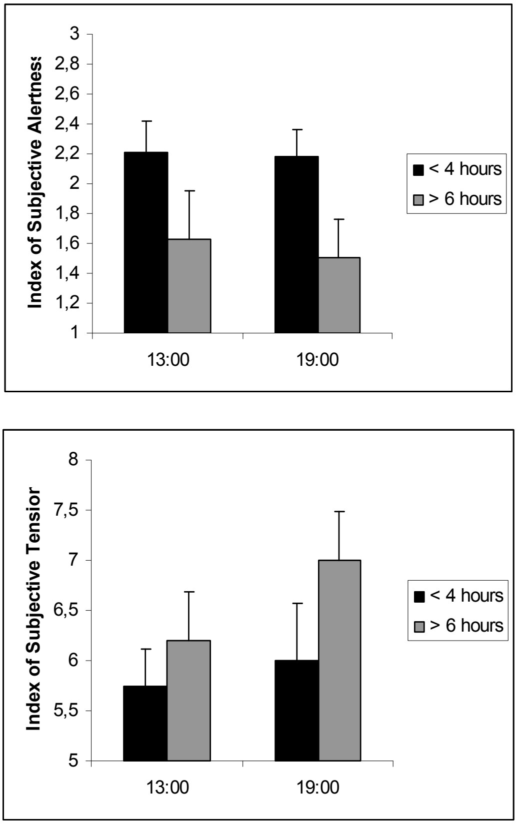

Figure 2. Mean (+/-SE) subjective alertness (upper pannel) and tension (lower pannel) in ATCs as a function of recording time (Mélan et al., 2007).

These data favour the interpretation that lower alertness reported by 12-h workers compared to 8-h workers on the early afternoon resulted from the fact that the former were on the second half of duty while the latter started their afternoon-duty (Tucker et al., 1998). Reduced day time alertness was observed on shifts starting late in the morning, though controllers had probably sufficient sleep on the night prior the shift. This raises the possibility that the chronic sleep deficit observed in shift-workers may, partly, account for decreased day-time alertness.

Further, both measures were negatively correlated, indicating that the lower ATCs quoted alertness, the higher they quoted tension. The data thus extend the findings of a circadian variation of subjective measures in ATCs and they favour the interpretation that in stress-related job-situations enhanced tension may compensate for decreased alertness (Thayer, 1989), thereby enabling the maintenance of safety. Further investigations will however be necessary to establish firmly whether ATCs' tension-ratings indicate a direct influence by environmental factors (i.e. hours at work, heavy traffic), or whether the observed variations are merely the consequence of their functional state, as indicated by the negative correlation between tension and alertness. Thus, air traffic control activities differ indeed between day- and night-work, as high traffic on day-time involves sustained periods of high task requirements and attentional demands, whereas low traffic during the night would favor boredom proneness and sleepiness (Costa, 1999; Lille & Cheliout, 1982; Luna et al., 1997).

In recent years, most studies exploring the impact of shift work on health and well-being have reported troubles in psychological and social well-being, performance efficiency and increased stress levels (Costa, 2003). Some of these issues will be highlighted in the next section by exploring the relationship between ATCs' physiological state and their performance efficiency during short-term recall of verbal material.

4. Complex interactions between task-related factors and ATCs' functional state

The shift-work literature shows that psychological measures differ not only according to time of day but also according to task characteristics, with high performance for tasks requiring rather automatic processing such as short-term memory task when alertness is low (in the morning), and high performance in more demanding tasks, relying for instance on long-term memory processing when alertness is high (in the evening). Laboratory studies reported indeed higher immediate recall in short-term memory tasks in the morning and enhanced delayed recall from long-term memory in the evening (Folkard, 1979; Folkard et al., 1976; Folkard & Monk, 1980; Monk & Embrey, 1981). Further, recall performance was reported to be higher in the morning when a recognition procedure was used, and in the afternoon when participants had to recall the text with a more demanding free recall procedure (Lorenzetti & Natale, 1996; Oakhill & Davies, 1989). Free recall would be cognitively more demanding as it involves an active search of memory traces in the absence of any cues, while item recognition would rely on less demanding item familiarity (Brébion et al., 2005; Mandler, 1980; Prince et al., 2005).

In light of the findings of the literature, it was important to investigate whether and to what extent the above-reported modality effect may be sensitive to alertness variations, but also to the cognitive effort required to remember the verbal material (Mélan, et al., 2007). ATCs' recall performance was recorded on different times of the day (01:00, 07:00, 13:00 and 19:00) while varying item modality (auditory or visual) during encoding and restitution, list-length (6- and 9-item lists) and restitution processes (recognition and free recall).

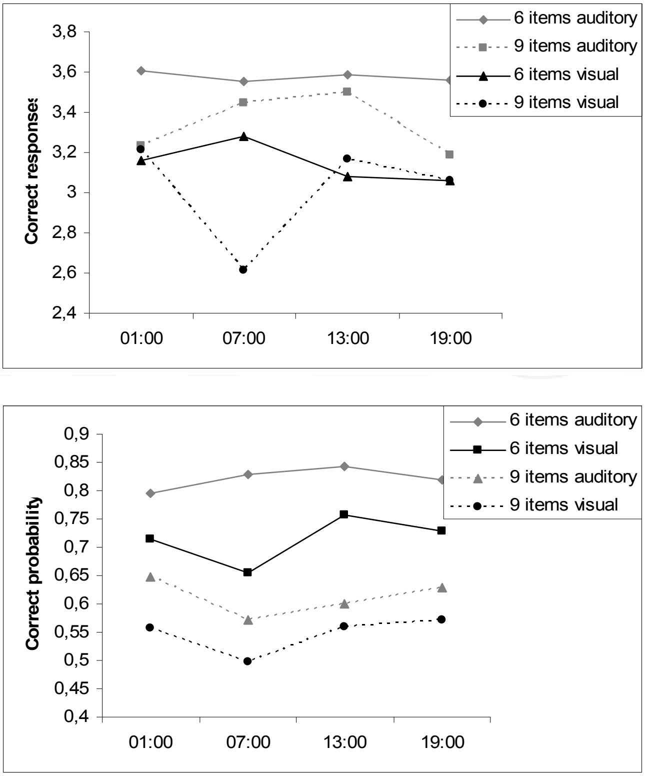

Figure 3. Mean number of correct responses in a probe recognition task (upper panel) and in a free recall task (lower panel) on each of four recordings according to the number of items presented (6- vs. 9-item lists) and presentation modality (auditory vs. visual; Mélan, et al., 2007).

Overall, ATCs' performance was lowest on 07:00 compared to 13:00 and 19:00, in particular for visual items, for the longer lists and in the free recall task (Fig.3). In consequence, when the tasks involved more demanding processing performance was decreased particularly when alertness was low. Interestingly, significant main effects occurred for time-of-day, list-length and modality with the free recall procedure, while the three variables interacted when restitution was based on a recognition procedure. In that case, performance dropped in the early morning only for visual 9-item lists, i.e. in the more demanding task conditions.

In the literature, differential time-of-day effects on participants' recall performance in recognition and free recall tasks were accounted for by similar processing differences (Folkard, 1979; Folkard, et al., 1976; Folkard & Monk, 1980; Lorenzetti & Natale, 1996; Oakhill & Davies, 1989). Accordingly, the finding of an overall effect on free recall but not on recognition performance may indicate that external factors (time of day) more readily impacted on ATCs' task performance when deeper processing was required to solve a task. As indicated above, item recognition requires less in-depth processing of the to-be-remembered material than free recall (Brébion et al., 2005; Mandler, 1980; Prince et al., 2005). Thus, task-dependent factors (modality, list-length and recall procedure in the present case) even further impact on ATCs' performance when their functional state is low.

5. Discussion

The main finding of the present contribution is that ATCs' performance depends in a complex manner from the task to be performed, but also from job organisation (shift schedules, shift-duration) and from physiological aspects (alertness, sensory and cognitive processing). Even though it is difficult to generalize between different job-situations, given in particular differences between activities, to-be-performed tasks and shift-scheduling, the data confirm findings reported in other safety-related job-situations for security agents in a nuclear power plant and for operators controlling satellites (Costa, 1999; Cariou et al., 2008; Galy et al., 2008). Working during the night causes a mismatch between the endogenous circadian timing system and the environmental synchronizers (the light/dark cycle in particular), with consequent disturbances of the normal circadian rhythms of psycho-physiological functions, beginning with the sleep/wake rhythm, and thus operators' alertness. In addition to the disruptive effects of shift work on performance efficiency, its impact on health and well-being are now well-documented (Costa, 2003; Siegrist, 2010). In this respect, some international directives have recently stressed the need for the careful organization of shift and night work and the protection of shift workers' health.

Elsewhere, the present findings favour the idea of a more general model to account for the complex interactions reported so far. In this regard, we recently extended Sweller's cognitive load theory elaborated in the educational field (Sweller, 1988; 1994), to a real-job situation (Galy et al., 2012).

5.1. Towards an integrated model of mental load during ATC?

Sweller defined three categories of cognitive load in order to embrace the complexities of a given task, the conditions in which it is performed, and subject-related variables. "Intrinsic cognitive load" refers to the load induced by the material to be processed, such as task difficulty that is defined in particular by the number of items to be processed, and by item interactivity (Ayres, 2006; Kalyuga et al., 2003; Sweller & Chandler, 1994). "Extraneous mental workload" refers to the load induced by external factors, including work situation, work organization, time pressure, and noise (Sweller, 1994). Finally, "germane mental workload" corresponds to the load induced by conscious application of strategies to solve tasks more easily (Schnotz & Kürschner, 2007). We showed an additive effect of intrinsic load (task difficulty) and extrinsic load (time pressure) factors, and that this effect was only observed in the morning. In other words, when participants performed a difficult task under high time pressure in the morning, when alertness and thus available mental resources were low, they probably had to use specific strategies generating germane load. This sequence of events would have led to decreased performance in the morning, while no such effect was observed in the afternoon, when alertness and thus available mental resources were high.

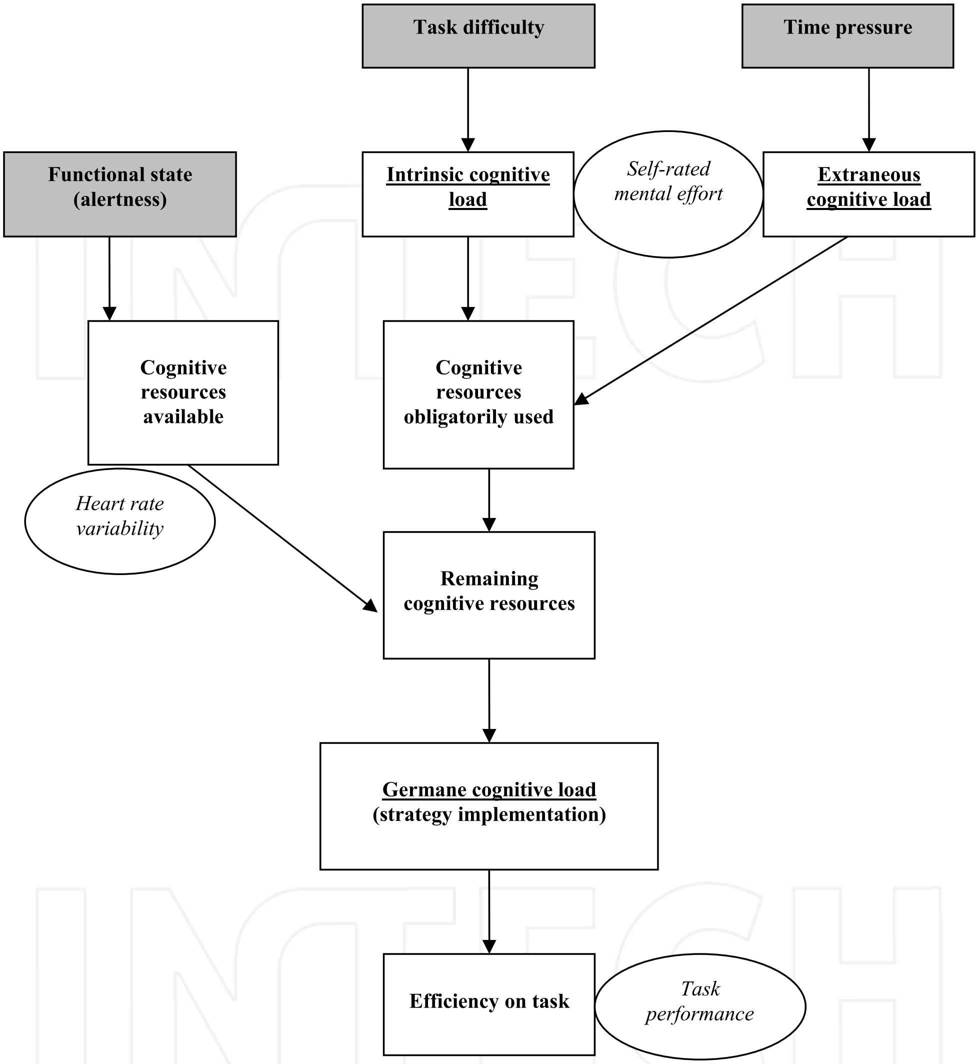

Figure 4. Graphic representation of putative relationships between cognitive load factors and cognitive load categories (Galy et al., 2012).

This model, summarized in figure 4, further indicates that the different cognitive load measures used in the study, i.e. subjective measures (self-rated effort), behavioural measures (correct responses) and psychophysiological measures (heart rate variability) display a differential sensitivity to the three kinds of load factors investigated. More especially, heart rate variability increased with germane load, operationalized by high self-reported alertness, whereas participants' self-rated mental effort was sensitive to both extrinsic and intrinsic load and task performance was determined both by alertness and by an interaction between task difficulty and time pressure. The latter results stress the difficulties encountered in order to identify a reliable measure of cognitive load on one hand (Backs & Seljos, 1994; Brookings et al., 1996; Carroll et al., 1986), and suggest that it may be hazardous to generalize the proposed model to other situations, on the other hand.

With these limitations in mind, it may nevertheless be challenging to test the mental load model in ATCs, given that the findings reported in the previous sections indicate how work organization (shift schedules, shift-duration) affected alertness (germane mental load), and that when ATCs' alertness was low, their mnemonic performance was lower in the demanding task conditions (intrinsic mental load). Further, as conflicts between aircrafts require ATCs to make the right decisions under high time pressure and to give ground-to-air instructions in a limited time, it seems indeed worthwhile to include this extrinsic load factor to a more integrative approach of mental load generated during ATC activities.

5.2. Experimental designs to explore ATC activities

Experimental paradigms like the ones used in the studies reported in this contribution may be regarded as simplified models of real-life activities. As such, the results reported may be of interest for ATC activities involving similar cognitive processes than those explored in the experimental paradigms. This is in particular the case for task-related factors, as the influence of such factors may only be demonstrated in controlled study conditions. In this regard, experimental approaches are complementary to *in situ* observations, which point to the relevant aspects to be explored more systematically by using experimental designs.

Further, the observations reported here were performed while ATCs were in their habitual work environment and work conditions. In contrast, in a number of field studies subjective data across the 24h-day are collected retrospectively, i.e. participants are asked to rate these measures on a single session by remembering what they perceived for instance during the night or during the morning shift. In contrast, subjective and performance measures reported in the present contribution were collected in real-time fashion, in order to gain some insight into ATCs' cognitive abilities in real-job conditions. This is particularly important when investigating job-activities performed on a continuous 24h-day, like ATC. The data reported here clearly show that shift-work features (time-of-day and time-on-shift) are indeed critical factors that impact not only on operators' functional state, but also on a number of psychological measures. ATCs' information processing ability is crucial for the safety of the air traffic management system as well as for the sector capacity of a given complexity in a particular time driving the overall system performances.

The present findings may be relevant to ensure productivity and/or safety in job-situations involving supervisory control, and in particular ATC, all relying on processing visual and auditory information from various sources on control panels and interfaces. The present findings suggest that short sequences of auditory information would less readily tax controller's processing capacities than longer sequences and/or visual material. As stated by

Frankish (2008), all models of speech perception incorporate some form of auditory short term memory, because speech comprehension requires the integration of information from successive elements. The findings reported here may thus be useful for various control operations and in particular during conflict resolution, when controllers' memory span may be more readily taxed. As shown by several studies, short-term recall of navigational messages decreases when message length increases beyond three commands (Wickens & Hollands, 2000; Barshi & Healy, 2002; Schneider et al., 2004). Taken together with several other studies, the present results may also be useful for ATC selection and training, as they stress the importance of using tests that manipulate, in addition to the more traditional quantitative aspects of memory, more qualitative parameters, such as presentation modality or information type and aircraft status (Gronlund et al., 2005; Means et al., 1988).

ATC, like several other safety-related job-activities rely preferentially on visual interfaces, most probably because graphical representations enhance the understanding of complex principles or spatial relations, for instance flight direction, speed and other information that an operator needs to synthetize in order to solve conflicting situations for instance. Within the auditory stream, successive items are strongly associated; in contrast, in the visual modality, it is simultaneously presented items that are strongly associated (Penney, 1989). Speech, with its linear progression through time does not bear these properties. In addition, sound and speech generate considerable noise when compared to silent reading of messages or integration of graphical representations.

However, for precisely the same reason, i.e. the disturbance induced by auditory information, this modality is typically used for alarm devices, as one cannot avoid an auditory signal. Indeed, the physical nature of sounds, i.e. waves that cross space in all directions, ensures that this kind of information automatically reaches and stimulates the auditory receptors and is transferred thereafter to the auditory cortex. There is thus a pretty good chance for heard messages or signals to be processed, even without paying attention to one's environment or when a subject's motivation or alertness are decreased for some reason. Furthermore, in addition to a specific activation of the auditory system, sounds also induce a non-specific activation of the nervous system, both the autonomous nervous system as evidenced for instance by increased heart-rate, and the central nervous system, as indicated by enhanced arousal. On contrary, written messages may be processed by the visual system only once a subject has oriented his/her gaze on the specific location where the message has occurred. Thus, unless the operator turns his/her attention to a particular location on a radar screen, he/she will not be able to appreciate whether for instance some airplane may be in a difficult position. Research concerning participant's focus of attention that would reflect conscious awareness and its relation to visual working memory tasks have been reviewed recently (Cowan, 2011).

In light of these considerations it appears that supervisory control greatly benefits from a well-weighted combination of visual representations of complex multi-dimensional data and auditory presentation of essential information which have to be maintained in a short-term memory for problem resolution.

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