Analysis of Dynamic Performance Data for the Assessment of Cognitive States: Results from Aviation, Assembly Tasks and Maritime Transportation

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Abstract

The rapid development and application of biometric recording devices has resulted in a plethora of human performance data in various industry settings. This article will demonstrate how the data generated by these recording devices can be used for inferring cognitive states in a variety of field settings and thus applied complementary to traditional data collection methods. The authors will present results from several studies demonstrating how data from portable motion and eye tracking devices can be used to assess three main aspects: the transition between safety-relevant cognitive coping strategies by pilots in aviation, the onset and time-based development of worker mental fatigue in assembly tasks and the time-based impact of situation-induced affective states on visual attention and decision-making in maritime transportation. Furthermore the paper outlines the underlying theoretical framework (the cognitive processing loop; Sträter (2005) Cognition and safety: An integrated approach to systems design and assessment. Ashgate, Aldershot). The benefits of this kind of approach will be demonstrated by showing how work systems can be improved by providing a better fit between cognition and workplace design.

Keywords

Mental fatigue • Coping mechanisms • Affective states • Assembly tasks • Aviation • Maritime transportation

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1 Introduction

Although the optimization of physical work demands has been a priority issue in the wake of the demographic change across various industry sectors in Germany, the optimization of work for cognitive demands is still very much work-in-progress. One of the main reasons being, that the assessment of cognitive states still poses significant challenges. As they mostly provide "snapshot" representations of cognitive states, traditional subjective, self-report measurements (e.g. questionnaires, interviews) are poorly suited for addressing the fluid and dynamic nature of human cognition (questionnaires), or are vulnerable to known distortions of memory (e.g. interview data). Advances in the technology of portable performance measurement provide a promising approach for addressing these types of issues and provide a complementary view to traditional methods.

One additional question that affects the design of cognitive work and the respective supporting systems consists in the explanation and understanding of the interdependency of affective responses and information processing and its impact on observable performance. Affect and emotion are acknowledged as aspects of everyday work that influence human performance [13, 23]. Designing work systems adapted to affective responses recently has attracted the attention of some scholars as a way to improve system and equipment design beyond usability and user satisfaction [9]. However, the impact of affective states on behavioral responses in the context of dynamic monitoring processes and system control has been rather marginally investigated to the present day [7]. One reason for this may lay in lack of appropriate methods and the inherent difficulty of modeling and integrating the potential impact of affect-related factors on—cognitive—performance. Most importantly, the fringe presence of affective phenomena in human factors research may be associated with a normative view of the role of affective and emotional states in the behavior of rational actors in the working context. Affects are considered as mostly negative interferences at the cost of rational decision-making and behavior, and hence are treated as unwelcome and unacceptable behavioral by-products that should not be there at the first place.

Despite this persistent view, affective phenomena constitute integral features of everyday life and everyday work [11, 23]. As such they should not be treated in a normative but rather in a pragmatic, descriptive manner. Research should focus on the assessment and analysis of the specific ways that such phenomena drive behavior especially in safety-critical situations.

Several studies will be presented how dynamic performance data can be used to address different issues related to cognitive states.

2 The Cognitive Processing Loop as an Explanatory Model for Dynamic Human Performance Data

The cognitive processing loop (CPL) is a framework for describing and modeling human information processing and relating it to human performance [23]. The CPL consists of several main components (Fig. 1):

- Human perception through sensory organs.
- The central comparator, which aligns the sensory input to the experiences and concepts of the human by minimizing dissonance between the internal world and the external world.
- The emotional system, which strongly influences the evaluation of sensory information and cognitive processing though affective activation.
- The vegetative nervous system which regulates the bodily functions.
- The motor system, which is involved in movement execution.

As the term ‘loop’ in CPL indicates, the information processing is treated as an iterative process. For simple single-loop stimulus-response tasks, the reaction times stated in the model are applicable: 50 ms for processing sensory information, 100 ms for evaluation and 50 ms for motor execution which leads to action.

The different studies are associated with different aspects of the CPL (Fig. 1):

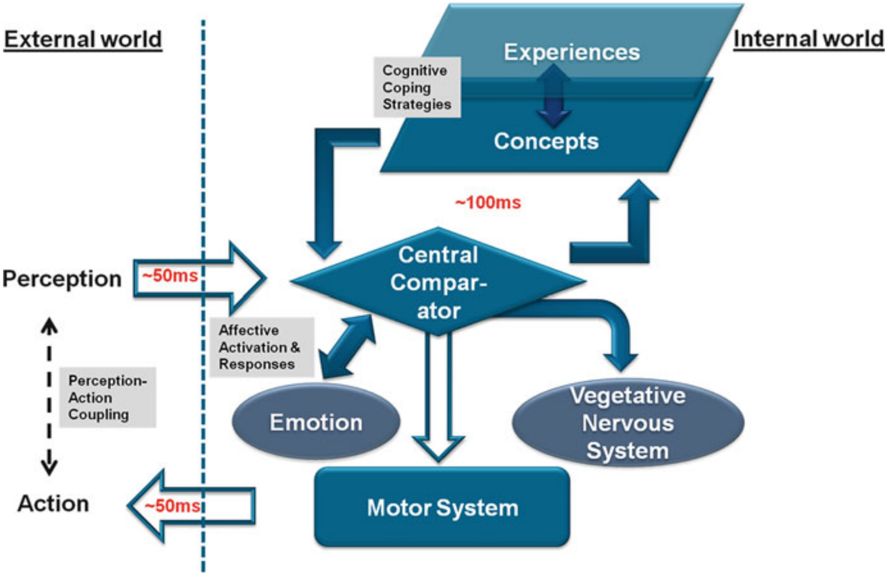

Fig. 1 The different research activities (*grey boxes*) addressing different aspects of the cognitive processing loop (CPL, [23])

- The first study from the aviation domain demonstrates how cognitive coping styles change over time given different task-demands. Via eye-tracking, the way how pilots use their concepts and experiences can be evaluated e.g. when noticing an engine failure.
- The second study taken from assembly work demonstrates how the patterns of time-based coupling of human perception, information processing and motor actions can be related to the issue of mental fatigue
- The third study from the maritime domain demonstrates how information processing is related to affective responses and how the latter in turn influence human perception and performance (as evident in eye-tracking data).

3 Analysis of Eye-Tracking Dynamics in Aviation: Cognitive Coping Strategies

In order to assess cognitive coping strategies in aviation, we have to move from traditional eye-tracking data to the analysis of eye-tracking dynamics [1]. A short summary on what is meant by cognitive coping will be given.

Human performance is always rational from the actors' point of view. In other words, people use their knowledge to pursue their goals; therefore a particular course of actions always makes sense from the practitioners' perspective at a given point in time [24, p. 16]. In a seminal paper, a cornerstone of this reasoning was defined—satisficing [21]. In essence, satisficing means that is not feasible for the human to process all of the relevant information to find the optimal solution in information-rich environments due to tight resource constraints. Instead, humans adopt a stance which is described as satisficing—they process information in such a way that solutions are produced which may not be optimal but rather "good enough" to be delivered in a timely manner. Otherwise the human would be constantly occupied with processing of information in order to find a perfect solution, an (reactive) approach that is not applicable in complex work places. As it is not possible for the human to process all relevant information, any actor essentially has to base his or her actions on an incomplete picture of the overall situation.

Therefore the human performance is always approximate in nature, as humans have "fill the gap" of their incomplete picture of the working environment by relying on heuristics and trade-offs [12, p. 93–94]. This produces variability in human performance, which often goes unnoticed, as it in the vast majority of cases leads to the desired results. However, in very rare cases performance variability may be associated with undesired outcomes, if the assumptions behind trade-offs or heuristics are violated (e.g. due to unanticipated complications or very unusual events).

Conversely, if human performance is approximate, that is, characterized by necessary short-cuts and heuristics, this should be reflected in the way human operators interact with their working environment and react to changes and disturbances.

Based on this reasoning, a study was conducted to assess the impact of an air-traffic control (ATC) information display for airborne separation on the performance of commercial pilots. Ten male pilots from a major German airline flew a safety-critical flight scenario in a full flight simulator using an ATC display in addition to the usual cockpit layout. An expert rating pilot trained by the airline scored their total performance.

The flight route chosen for the investigation is a standard scenario for the pilots and consists of a flight from Athens to Heraklion. On route, after ~60 s of flight time, the pilots receive a traffic warning of a potential head on collision with another aircraft in the ATC-display followed directly by the sudden onset of an engine failure. Thus, the pilots have to resolve the traffic conflict with the other flight on collision course and notice/react to the engine failure at the same time. In this situation, the pilots are facing a goal conflict: Should they focus on resolving the collision warning or on the engine failure? Here, the engine failure should be treated as the priority issue over the traffic warning following the principle of "fly the aircraft first" [3, 20]. The results of the study demonstrated that some pilots focused on the ATC display and thus did not notice the engine failure in time [3, 20].

The difference in coping styles between the pilots who noticed the engine failure right away/without delay and the pilots who did not were examined using NMDS representations of respective eye-tracking data: The non-metrical multidimensional scaling technique is an ordination technique (NMDS) that produces a graphical representation of a distance matrix by preserving the original distances as well as possible. Using a correlation matrix of eye-tracking data on Areas of Interest (AoI) as distance matrix, a two-dimensional representation of the correlation between the visual focus on the information sources can be calculated [22]. The closer the points are in the NMDS representation, the stronger the correlation between the gazes on the two information sources, that is, the stronger the common visual focus on them. This representation can thus reveal the division of visual attention associated with this coping strategy of prioritizing the traffic warning over the engine failure.

In order to create the representation, the eye-tracking data of a pilot that did not notice the engine failure in time has to be separated into meaningful segments that provide insight into the coping process associated with the onset of the traffic warning and the engine failure. The change in the strategy applied by the pilot is clearly visible with the onset of the collision warning as shown in the left hand side NMDS representation of Fig. 2. The autopilot, the ATC-display with the traffic warning and the central console are in joint visual focus, while the other displays zone out of visual focus.

The right hand side NMDS representation of Fig. 2 shows the visual attention after the pilot has noticed the engine failure, about 20 s after its onset. The primary flight display (PFD) and the engine and warnings display (E/WD), both relevant for handling the engine failure, are in visual focus—together with the ATC-display. Visual focus on the latter is not required if the principle "fly the aircraft first" is followed. This means, that the most safety-critical issue is a pilot focusing on resolving the traffic warning although the engine failure has been identified.

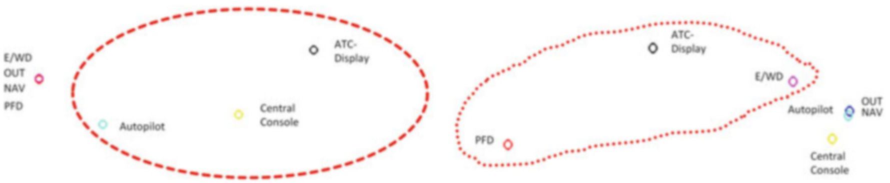

Fig. 2 Left-hand: After the traffic warning, information sources relevant for collision avoidance are focused (*red circle*). Right-hand: The pilot notices the engine failure occurring directly after the traffic warning late; however still also focuses on ATC-display (irregular red shape) [Note: the NMDS representation is dimensionless]

Using eye-tracking, this issue can be identified by the fact that visual attention is directed away from the most pressing task—the handling of the aircraft—to resolving the traffic warning.

Thus, the NMDS representation shows the different coping strategies associated with safety-critical changes (traffic warning and engine failure) in the work environment. In terms of the CPL, coping strategies are cognitive actions steering the visual attention towards those perceptual elements of the external world that fit the actual elements of the conceptual level.

4 Eye-Tracking for Assembly Tasks

Most industrial assembly tasks are characterized by simple manual tasks performed by workers. The mental effort required for performing these kind of tasks is characterized by recognition-action-coupling also termed “object related actions” (ORAs, [16]): The worker’s task is grasping objects and place them on defined positions. Performing ORAs requires spatial orientation of the whole body and the recognition of task-relevant objects. Spatial orientation and recognition of task-relevant objects in turn requires cognitive processing of visual information by the worker. Before performing an ORA, the action relevant object therefore is first fixated with the eyes and then grasped with the hand.

The mental workload associated with simple manual tasks is comparatively low (underload). Therefore, the mental fatigue of the workers usually stems from mental underload as a consequence of the repetitive characteristics of the tasks.

Commonly, two types of methods are applied in order to measure mental fatigue: Either measuring primary task performance or by subjective response (e.g. questionnaires). Measuring mental fatigue by primary task performance seems to be inadequate because operators are able to compensate for low workload by increasing their effort to maintain vigilance. Therefore, performance outcomes of simple manual tasks are no adequate measures for mental fatigue. The measurement of mental fatigue by subjective response (e.g. questionnaires) is also problematic. It may produce distorted results as performance and perception tend to deviate. An alternative is the use of physiological parameters to assess mental fatigue. This seems as a promising approach [8]. We follow the hypothesis that cognitive processing time differs depending of the prevalence of mental fatigue. We assume that the time between fixating and grasping is the time required for cognitive processing of the information for controlling the body's motor functions. We call this time span eye-hand-latency (EHL; [19]). In the course of several studies, the visio-motoric measure EHL in milliseconds (ms) was tested as an indicator for mental fatigue in simple manual tasks [14, 15]. Both studies indicate a fatigue-related pattern of the EHL over time: At the beginning of the shift the EHL is by trend shorter than at the end of the 8 h shift.

In both cases, the measurements were done for the complete working shift and we compared similar tasks: The tasks studied were conducted in u-shaped production cells with several machines served by one worker. The type of production cells under study were organized following the chaku-chaku approach. It is a concept originating from the philosophy of the Toyota production system. The Japanese term "chaku chaku" means "load load" and defines the workers task very accurately: stepping from machine to machine and loading and unloading objects manufactured automatically by the machines. Although the tasks in focus of the studies [14, 15] are very similar, there are some characteristic differences which should be pointed out. They require a different range of actions to be performed. In the first study, the work consisted of simply loading and unloading objects from the machines. If a technical disturbance occurs during work, it is strictly prohibited to take appropriate action to eliminate the interference by the operator himself. In the second study, besides loading and unloading objects, the elimination of technical disturbances was explicitly defined as part of the operator's task. The workers were specifically trained for eliminating disturbances.

For both cases a *t*-test for independent samples was conducted to compare the EHL values for the beginning and the end of an 8 h shift. Table 1 shows the results for the work system with very simple tasks.

In this case, the test confirmed an effect on α-level of 0.1 ($p = 0.09$): The EHLs at the end are longer than in the beginning. Cohen's d (0.35) and the Bravais-Pearson Correlation (Effect $r = 0.19$) confirm a slight effect [14].

The results for the enriched task with the broader range of activities are shown in Table 2. Here, the *t*-test is significant on α-level of 0.05 ($p = 0.011$). The Bravais-Pearson Correlation (Effect $r = 0.28$) confirms a slight to medium sized effect and Cohen's d (0.59) confirms a medium sized effect [15].

There is a difference in the effect size between the two tasks. This may have been due to the differences in the work content between the simple and the enriched task. The simple task leaves the working person very little freedom for action which means that there is a very low variation in task performance for the worker. The person performing the task is forced to follow the machines step by step and to load and unload the objects. The worker does not necessarily need to know anything about the production process and the technology at all. The elimination of technical disturbances is prohibited for the worker. In the case of a technical disturbance the operator is required by management order to call a member of the maintenance staff who will eliminate the interference.

Table 1 *T*-test for independent samples for the simple task [14]

Groups	Count	Mean (ms)	SD	Variance			
Beginning of shift	22	476.36	229.58	52709.95			
End of shift	27	854.81	1431.99	2050602.84	Standard error	*t*	*df*
Pooled				1157927.30	279.90	1.35	47
		df	27.63				
		p-value	**t-crit**				
One Tail		**0.09**	**1.31**				

Table 2 *T*-test for independent samples for the enriched task [15]

Groups	Count	Mean (ms)	SD	Variance			
Beginning of shift	37	569.72	303.95	92391.59			
End of shift	30	764.00	360.13	129693.79	Standard error	*t*	df
Pooled				109034.11	82.58	2.35	65
		df	56.88				
		p-value	**t-crit**				
One Tail		**0.01**	**1.67**				

The enriched task is more diverse compared to the first one. The elimination of disturbances is explicitly part of the work task and the workers had the appropriate qualification to do so. This additional task may contribute to task diversity which may be the cause of the differences in effect strength measured in the two studies.

The hypothesis is that we measure a mix of mental fatigue and fatigue like states. In order to gain better understanding of the effects, the concepts used in the study have to be differentiated further. This is the difference between states of mental fatigue and fatigue-like-states [10]. However, two studies provide an insufficient basis for verifying this conclusion and thus further studies have to be conducted. To study these combined effects, indicators are needed which allow the differentiation between mental fatigue and mental states similar to fatigue.

The eye-hand-latency has a direct correspondence to the CPL. A change in the latency can be directly related to the delay in the alignment of concepts with the external perceptual demands, hence mental fatigue can be seen as a result of fatigued elements of the CPL.

5 Affects and Cognition, Time-Bound Effects in Eye-Tracking

Affects are ubiquitous aspects of behavior as they represent constant evaluations of the actual or anticipated relationship between the human and the external world. Such evaluative processes take place on a conscious or a subliminal level and enable humans to adjust their behavior in a respective manner in order to establish an acceptable match between the interacting environmental demands and the behavior-driving goals and choose action [5, 6, 18, 23]. It is reasonable enough to consider working behavior as a subset of overall human behavior. Accepting that the above assumption is true, one can argue without much controversy that affect ubiquity is also true for work-related behavior and in-work performance. In agreement with a descriptive view on affects, the main questions that need to be addressed consist in the specific fashion in which affective and cognitive responses are related to each other; the direction of the relation and the respective behavioral adaptations with regard to distinct affective states and situational demands; and the behavioral parameters and levels on which the manifestation of affective responses can be observed and documented in a valid manner. Athanassiou [4] addresses these issues within the scope of a PhD activity conducted in the Department of Human and Organizational Engineering and Systemic Design at the University of Kassel to be published soon. The research has been driven by the assumption that cognitive and affective functions are tightly interrelated [23]. Thus they underlie similar principles of activation that drive information processing and behavioral adaptations. However, additional overtly affective load may induce distinct—observable—adaptation responses, which will be reflected in relevant behavioral parameters, such as visual attention. This fundamental research question was tested empirically in the context of simulated ship management tasks using eye-tracking measurements.

The empirical study was conducted in the full-mission ship handling simulator facility at Jade University of Applied Studies. N = 13 students of nautical studies participated in the study. Participants were assigned to two task-based scenarios, of which, one was designed to employ situation-induced affect through task-integral trigger events. The specific trigger event considered within the scope of this article was associated with acute time and space challenges for the safety of the operational process (crossing situation with another vessel in shallow and narrow waters and restricted available time for evasive measures). Affect-inducement in the affective treatment condition was operationalized through the behavior of the traffic "opponent", which was characterized by uncooperative and face-loss communication.

A mixed 2 × 5 factorial design was employed for the empirical study. The two levels of the between-group factor represented the two experimental conditions under consideration, i.e. task performance with additional affect-inducement versus "normal" task performance (control condition). The within-group factor represented the subsequent 5 min directly after the onset of the affect-inducing trigger event. Visual attention has been operationalized through measures of fixation duration and fixation dispersion towards crucial information sources on bridge as well as overall fixation shifts for the five consequent minutes immediately after the trigger onset of. The results concerning the view out/windscreen (due to the criticality of the information source for unexpected situations) and the aspect of overall fixation shift number will be briefly showcased.

The results of the mixed ANOVA (Pillai's Trace) showed a significant interaction between affect–inducement and visual attention over time (F (4, 8) = 4.581, $p = .032$, partial $\eta^2 = .696$) in terms of fixation duration rates towards the view out of the windscreen (Fig. 3). This result suggests that individuals made distinct use of the information source when faced with explicit affective load in conditions of severe time constraints and the need of fast decision-making. Visual information search and consultation were directed more intensively towards the outside world and not its representations (i.e. Radar screen) during the 3rd and 4th minutes after the trigger onset (when the situation developed in a manner that posed severe threats for vessel safety). Lower rates for the rest of the time suggest an increased ability to distribute visual attention towards available information in a less fixated manner. The behavior was inversed (and somehow with more moderate "deflections" during time interval) for individuals facing a similar situation with only the respective cognitive load, hence suggesting differences in necessary control efforts in order to adjust to the situational demands due to the affect inducement.

The same statistical procedure was followed for the analysis of potential effects of the affect-inducement on the overall fixation shifts towards all information sources available in the bridge operational environment over time (Fig. 3). The results showed a main effect of time on fixation shifts for both conditions (F (4, 8) = 3.843, $p = .050$, partial $\eta^2 = .698$) suggesting an increased visual activity in the progress of time as a consequence of the situational conditions of operating action. However, an additional nearly significant main effect of the scenario-based affective treatment on the overall fixation shifts towards information sources on bridge was obtained by the statistical analysis (F (1, 11) = 3.878, $p = .075$, partial $\eta^2 = .261$). This result suggests that affect-inducement was associated with an increased need for fixation shifts towards and between information sources on bridge right from the very onset of the trigger event. The observed difference between the conditions indicates increased efforts to maintain control and hence distinct adaptive performance of human operators that can be assigned to the specific impact of task-integral affect and to the subsequent affective responses during dynamic, time-bound task performance.

The maritime study showed the interrelation between the cognitive and the affective parts of the CPL. Cognitive dissonance, as a result of the central comparator, impacts the cognitive quality of decision making and in parallel this results into an affective reaction on the dissonance.

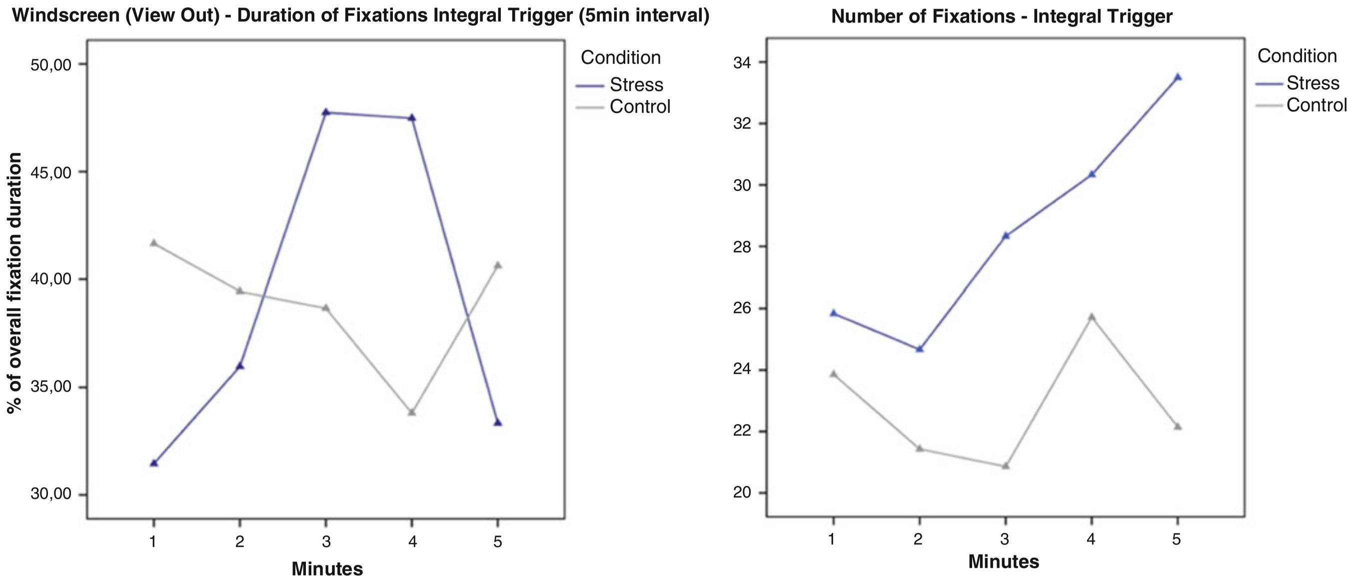

Fig. 3 Mean values for fixation duration rates towards the view out (*left*) and number of fixations towards information sources on the bridge (*right*) within the 5 min interval immediately after the onset of the affect-inducing trigger event

6 Discussion

This article has described three different research activities using dynamic performance data for inferring cognitive states based on the cognitive processing loop (CPL).

- The aviation study demonstrated how the NMDS-representation can be used to capture dynamics of eye-tracking behavior to derive cognitive coping strategies when facing adverse conditions (e.g., traffic warning/engine failure in aviation). The cognitive coping strategies are related to the way that pilots align the events in the external world (the engine failure/traffic warning) with the internal world (previous experiences and concepts).
- The analysis of eye-hand latency (EHL) for assembly tasks demonstrated how mental fatigue-related effects can be identified in assembly tasks in field settings by analyzing the eye-hand-latency over time. The EHL is defined as the time needed to couple perception and action in the CPL.
- Finally, the maritime study showed how eye-tracking performance can be linked to the reciprocal relationship of affective and cognitive states. The results allow for understanding the specific ways, in which affect-eliciting instances and the respective affective responses influence the way that human operators interact with their work environment.

The studies showed how performance date with the underlying model of the CPL can serve as a basis for better task or workplace design:

- Different coping strategies can be measured and plausible courses of action can be identified e.g. to develop appropriate qualification programs or support-systems based on this information,
- Task-design can be enriched by taking the effects of mental fatigue over time into account,
- The effects affective responses on task performance can be used to raise awareness for, to enhance the behavioral repertoire of the human element, or to guide system design efforts in a manner, which will ensure that the work system stays resilient even when facing emotionally challenging situations.

7 Outlook

As the aviation study showed, a NMDS-representation can yield satisfying results regarding the differentiation of eye-tracking dynamics before and after critical events. However, one open issue is the appropriate aggregation of the results: How should the NMDS-representations be compared between individuals? That is, what are appropriate statistical methods for aggregating and comparing the differences in the NDMS representations? Furthermore, the NMDS should ideally be applied is such a way that it enables the analyst to identify coping styles without prior knowledge of critical events; i.e., for cases in which it is unknown when systematic changes in coping styles will occur. Once this issue is solved the next question is, which level of resolution or scope (time window) should be used to calculate the NMDS representation in order to capture the changes in coping styles. Ideally, a systematic application of the NMDS should answer these questions. These issues will be addressed in the course of a current PhD-activity funded by the EU and Eurocontrol Network HALA!—Towards Higher Levels of Automation in Air Traffic Management [2].

The implementation of eye-tracking in the context of task performance in the maritime domain allowed for insights concerning the interdependency as well as the distinctiveness of affective and cognitive processes in in-work situations. However, the affect-cognition reciprocal relationship and mutual influencing are not restricted to situations of which affect is a clear and integral constituent. Moreover, they may refer to situations, on which affective responses constitute the result of carry-over effects of affect, but with a similar relevance for attentional activity, thorough information processing and risk perception [17, 23]. In addition, different situational aspects, such as expertise, will lead to distinct appraisals of the situation at hand and thus to distinct affective experiences with different attentional and action strategies and responses. Eye-tacking data can be a powerful source of information in regard to the assessment of these indirect effects of distinct affect-laden situations in the course of events and hence provide empirical validation and guidance towards an integration of affect in modeling human performance.

Finally, the link between human factors and affective psychology does not have to be restricted to dynamic data on the level of individual performance. A great importance is ascribed to the issue of teamwork and safety performance in human factors research as well as in practice. Hence, it is reasonable to guide efforts towards the exploration and derivation of relevant knowledge concerning the interrelations of affective responses and safety-crucial aspects of performance on the team level. Eye-tracking data provide only one option for such endeavors. Observational data, based on sound practice-relevant criteria and collected through domain-specific and well-constructed methods, provide another option, which allows for significant complementary information regarding the respective question of assessing affect-related effects on performance. Athanassiou [4] is addressing both issues in his current research activities.

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