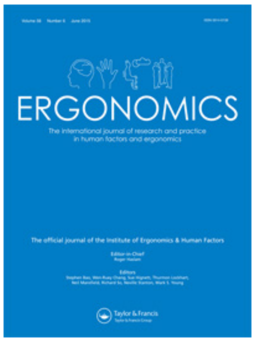

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The process of processing: exploring the validity of Neisser's perceptual cycle model with accounts from critical decision-making in the cockpit

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The perceptual cycle model (PCM) has been widely applied in ergonomics research in domains including road, rail and aviation. The PCM assumes that information processing occurs in a cyclical manner drawing on top-down and bottom-up influences to produce perceptual exploration and actions. However, the validity of the model has not been addressed. This paper explores the construct validity of the PCM in the context of aeronautical decision-making. The critical decision method was used to interview 20 helicopter pilots about critical decision-making. The data were qualitatively analysed using an established coding scheme, and composite PCMs for incident phases were constructed. It was found that the PCM provided a mutually exclusive and exhaustive classification of the information-processing cycles for dealing with critical incidents. However, a counter-cycle was also discovered which has been attributed to skill-based behaviour, characteristic of experts. The practical applications and future research questions are discussed.

Practitioner Summary: This paper explores whether information processing, when dealing with critical incidents, occurs in the manner anticipated by the perceptual cycle model. In addition to the traditional processing cycle, a reciprocal counter-cycle was found. This research can be utilised by those who use the model as an accident analysis framework.

Keywords: critical decision method; perceptual cycle model; schema theory; aeronautical decision-making; qualitative analysis; validity

1. Introduction

Neisser's (1976) perceptual cycle model (PCM) structures the interaction between a person's internal schemata (or mental templates) and the environment in which they work. Acknowledging the interaction between person and world has resulted in it becoming a popular theoretical perspective in ergonomics research, with applications in the areas of naturalistic decision-making (NDM), situation awareness (SA) and human error to name but a few (Plant and Stanton 2013a). The model has been applied in a number of domains, including aviation (e.g. Plant and Stanton 2012a, 2012b, 2013b), road (e.g. Salmon et al. 2014) and rail (e.g. Stanton and Walker 2011; Salmon et al. 2013), and it underpins Stanton and colleagues theory of distributed situation awareness (DSA: Stanton et al. 2006; Salmon et al. 2008a, 2009a). However, to our knowledge, the PCM has not been formally validated. Whilst the model makes intuitive sense, it is not clear whether information flows in the manner suggested by the model (see Figure 1). This paper utilises interview data from 20 rotary wing (i.e. helicopter) pilots in order to validate the PCM. In doing so, it builds on a previous study by Plant and Stanton (2013b) in which the PCM was used as the basis for examining the process of aeronautical decision-making.

1.1 The PCM and its applications in ergonomics research

The PCM (Figure 1) is an information-processing model based on the idea of a reciprocal, cyclical, relationship between an operator and their environment. Internally held mental templates (schemata) are trigged by environmental conditions and direct perception and behaviour, thus our interaction with the world. The environmental experience can result in the modification and updation of cognitive schema, and this in turn influences further interaction with the environment. This ecological approach suggests that information processing is cyclical rather than linear, and active rather than passive.

The PCM provides a model of individual cognition based on schemata that are personal mental representations. But it recognises that cognition is extended beyond the individual because perception, decisions and actions are grounded within the context of the environment in which they occurred. The aviation industry has previously been criticised for studying judgement and decision-making out of the context in which it occurred, assuming that errors are the result of either technological or human failure, rather than the joint human–technology system (Maurino 2000; Hobbs & Williamson

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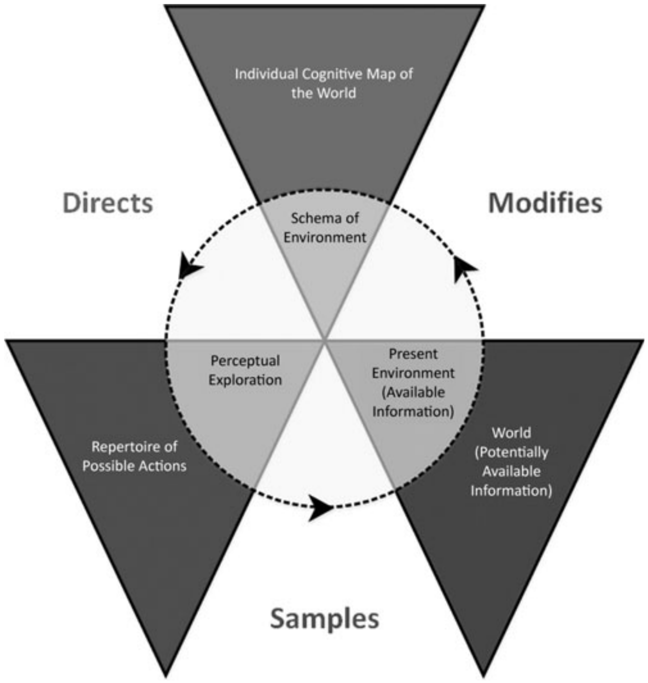

Figure 1. The perceptual cycle model (adapted from Neisser 1976).

2002). The recognition of both the individual and the environment has resulted in the model's popularity and endurance in ergonomics research. This view was shared by Smith and Hancock (1995) who argued that the usefulness of the PCM explanation lies in the interaction between operator and environment. This was echoed by Salmon et al. (2009a) who stated 'that the perception–action cycle together with Schema Theory offers a theory of everything' (p. 189), in that it explains the way in which the world constrains behaviour as well as how cognition constrains our perception of the world. The model encompasses both top-down and bottom-up information processing and explains how everyday behaviour is formed through a mixture of both approaches. As such, the model has been readily applied in the ergonomics discipline. For example, Smith and Hancock (1995) used the PCM as the foundation for their perspective of SA, arguing that 'the informed, directed sampling and/or anticipation capture the essence of behaviour characteristic to SA' (p. 141). Stanton et al. (2001, 2009) argued that the interactive nature of the PCM is good at explaining the dynamic aspects of SA and the collective behaviour of systems as a whole, as opposed to individuals. As such, Stanton and colleagues used the PCM as one of their underpinning concepts in their theory of DSA (Stanton et al. 2006; Salmon et al. 2009a). This approach argues that awareness is distributed across human and technological agents involved in collaborative activity (Salmon et al. 2008a).

Aside from being the foundation of theoretical perspectives, the PCM has also been applied as a basis for accident analysis across a variety of domains. The schema element of the model accounts for how we act in the world and consequently can explain what can go wrong, whilst grounding this explanation in the context of the work environment. Faulty schema or faulty activation of schema will lead to erroneous performance (Norman 1981). For example, Plant and Stanton (2012a) used the PCM as a framework to explain the decision-making processes of the pilots involved in the Kegworth plane crash. It was demonstrated that the combination of the schemata held by the pilots and the environmental information they were exposed to led to their erroneous actions of shutting down the wrong engine. In the railway domain, Stanton and Walker (2011) used the PCM to explain human information processing in train driving. In the instance of the Ladbroke Grove rail crash, Stanton and Walker (2011) demonstrated that, amongst other factors, the train driver displayed a number of schema-driven errors, including mode errors (erroneously classifying the situation) and data-driven activation errors (external events that cause the activation of schemata). Similarly, Salmon et al. (2013) used the PCM to explain the actions of the truck driver who failed to comply with a level crossing causing the death of 11 train passengers in Kerang, Australia. It was shown that the driver's failure to respond to the activated level crossing was caused by the activation of an inappropriate schema, i.e. a schema for the level crossing in a non-active state. This was developed through the driver's extensive experience of crossing the track when the level crossing was not activated. This then shaped the driver's perceptual exploration and he continued to cross the track as he perceived that the crossing was in a non-active state. Further environmental factors including the design of the crossing, sun glare and trees obscuring the train meant that the inappropriate schema was not overridden. Aside from averting performance errors, Neissen, Eyeferth, and Bierwagen (1999) argued that understanding schemata developed by operators can inform the design of training programmes and the programming of automation because schemata are based on operators' knowledge and skills developed through practice and are antecedents to successful performance.

1.2 Theoretical validity

In its linking of the mind to action to world back to the mind, the PCM offers a comprehensive framework making it a popular and enduring theoretical perspective in ergonomics. However, to our knowledge, the PCM has never been formally validated, it is assumed that the cycle of information processing occurs in the way that Neisser (1976) described it. Stanton (2002) questioned the amount of academic theory or verifiable evidence that many ergonomics methods and models are based on. Similarly, Salmon et al. (2009b) suggested that reliability and validity should be a critical consideration when selecting methods. Methods can be reliable (provide consistent measurement) without being valid (provide an accurate reflection of a phenomenon), but they cannot be valid without being reliable (Stanton and Young 1998, 1999). Whilst the discussion around reliability and validity is generally concerned with method selection, the importance of these in relation to theories should not be overlooked. Generally, methods and theories can either be analytical or evaluative (Stanton et al. 2013). The PCM can be considered an analytic model as it offers an understanding of the mechanisms underlying the interactions between humans and the machines they use or the environments they work in, whereas evaluative methods and theories estimate parameters of selected interactions between human and machines.

Specifically, within the context of aeronautical decision-making, O'Hare (1992) conducted an extensive review of the literature and concluded that studies on pilot decision-making have emphasised methodology rather than theory. For Ergonomists to continue to use the PCM with confidence as a theoretical foundation or an accident analysis framework, they need to be certain that the PCM offers a representative model of information processing. This is termed construct validity, which Annett (2002) defined as how acceptable a theory is and, in addition, the test of validity that needs to be established for analytic theories (Stanton et al. 2013). However, Annett (2002) has argued that the evidence of validity is hard to come by. Likewise, Robson (2002) stated that 'there is no easy, single, way of determining construct validity' (p. 102). Assessing validity of the PCM is particularly relevant considering the use of the PCM as a framework for data derived from accident reports when first-hand accounts may not be available (e.g. Plant and Stanton 2012a; Salmon et al. 2013). In these cases, ergonomics theories can be used to propose valid explanations for instances of behaviour, and therefore it is pertinent that the theory is valid as far as possible to ensure the accuracy of the description of behaviour (Salmon et al. 2013).

1.3 Aeronautical decision-making: case study for the validity of the PCM

The research presented in this paper has relevance to the validity of the PCM in general, but it is grounded in the context of aeronautical decision-making. The majority of aviation crashes are attributable to decisional, rather than perceptual or action errors (O'Hare 1992). The aviation domain epitomises the NDM environment in complex sociotechnical systems, in which decisions are made in environments characterised by limited time, goal conflicts and dynamic conditions (Klein, Calderwood, and Macgregor 1989). In such an environment, Plant and Stanton (2013b) advocated the importance of understanding the decision-making process, rather than decision outcome, in order to understand why actions and assessments made sense to the decision-maker at the time they were made, i.e. what conditions were present at the time of the event that may have influenced performance. This approach detaches from allocating blame at the operational end of events because human performance is considered inseparable from the context in which it takes place (Maurino 2000). Back in the 1950s, Simon argued that human rationality is bounded by design and operational features of environmental contexts (Simon 1957, 1959). This idea has evolved into the principle of local rationality, i.e. knowledge is intrinsically local and subjective so assessments and actions make sense given the operator's goals, current knowledge and focus of attention (Reason 1990; Dekker 2011). As such, behaviours can be explained by the situations in which they occurred. The interaction that is represented in the PCM between operator and environment allows for local rationality to be explained and understood.

It has been previously demonstrated that the PCM can be used to explain and understand aeronautical decision-making (Plant and Stanton 2012a, 2012b, 2013b). The following example demonstrates this in the context of dealing with a critical incident where all the screens in the cockpit went blank: the pilot held a schema, acquired through past experience, that the blank screens were likely to be the result of an electrical fault because the aircraft was known to have electrical glitches. This schema enabled him to search for confirmatory evidence, direct a course of action and continually check that the outcome was as expected (e.g. the first diagnostic attempt was to check for popped circuit breakers, which is a common cause of electrical glitches). The environmental information was unexpected (e.g. the circuit breakers were all fine and there were no obvious electronic problems), and therefore the pilot was required to source a wider knowledge of the world to consider possible explanations that directed future search activities (e.g. in other diagnostic attempts, the pilot consulted the flight reference cards and adjusted the brightness of the screens).

The current paper seeks to answer the question as to whether people actually process information as proposed by the PCM by validating the model with decision-making data. In doing so, it also builds on the case study presented in Plant and Stanton (2013b) and assesses the utility of the PCM at explaining aeronautical decision-making using data from 20 pilots. Whilst this research is grounded in the context of aeronautical decision-making, it holds relevance to other complex human–machine, safety-critical systems that characterise much of ergonomics research.

2. Method

2.1 Critical decision method

The critical decision method (CDM; Klein, Calderwood, and Macgregor 1989) is a semi-structured interview technique devised to extract the content knowledge of experts from a naturalistic setting. This is achieved through the use of cognitive probes as a tool for reflecting on strategies and reasons for decisions during non-routine situations. Since its development, the CDM has been extensively used in a variety of domains including emergency dispatch management (Wong, Sallis, and O'Hare 1997), critical-care nursing (Crandall and Gretchell-Reiter 1993), energy distribution (Salmon et al. 2008b) and aviation (O'Hare et al. 1998; Hobbs and Williamson 2002; Plant and Stanton 2013b). The method elicits knowledge for decisions that are devised through the recognition of critical information from the environment based on past experience and expertise. This focus on the interaction between individuals and their environment aligns the method with the ecological approach of the PCM. Furthermore, Salmon et al. (2013) suggested that the CDM is a suitable method for gathering information on schemata, which are notoriously difficult to measure (Plant and Stanton 2013a). The CDM elicits expert knowledge by asking people to discuss previous incidents they were involved with. Crandall, Klein, and Hoffman (2006) described the four phases for conducting a CDM interview: (1) incident identification, (2) timeline construction, (3) deepening probes and (4) 'what if' queries. Interested readers are directed to additional texts for the full CDM procedure (e.g. Crandall, Klein, and Hoffman 2006; Klein and Armstrong 2005; Stanton et al. 2013). A selected example of the probes is provided in Table 1.

The CDM can be criticised for its reliance on verbal reports, especially as retrospective recall is required and may occur sometime after the original incident (Klein, Calderwood, and Macgregor 1989). To address this issue, Plant and Stanton (2013b) assessed the retest reliability of the CDM with a time interval of over 2 years and it was found that there was no difference between data at Time 1 and Time 2 in 10 of 17 themes identified and differences in the remaining seven themes were marginal. The consistency of information over such a long time elapse can be attributed to the use of structured CDM probes as they result in the same questions being asked, thus similar responses are elicited (Klein, Calderwood, and Macgregor 1989). As such, the CDM may be used with confidence that it is likely to be a reliable method for collecting data on critical decision-making.

2.2 Participants

Twenty rotary wing pilots participated in the research and were initially recruited through an advert placed on the British Helicopter Associated website and then via word-of-mouth. Males made up 95% of the sample; this is in line with data from the Civil Aviation Authority (2010) indicating that female pilots comprise 5% of all UK airline pilots, a figure that is potentially less amongst rotary wing pilots. Twenty-five per cent of the sample was aged between 31 and 40 years, 40% was

Table 1. Examples of the cognitive probes used in the CDM.

Area	Probe
Goals	What was your specific goal during the scenario?
Decisions	What was the primary decision that you made?
	What features were you looking for when formulating your decision?
Information	What information did you use to make that decision?
	Was there additional information that you might have liked to assist your decision-making?
Experience	Was the decision made comfortably within your experience (why/why not?)
	Did your experience influence the decision that you made?
Expectations	Did you hold any expectations that influenced the decision-making process?
Options	What other courses of action were considered/available to you?
	How was one option chosen and the others rejected?

aged between 41 and 50 years and 35% was aged between 51 and 60 years. The pilots were all relatively experienced; flying hours ranged from 1150 to 13000 (mean = 5942, SD = 3304, median = 5000). The pilots were employed in a range of roles, including military, personal passenger transport, North Sea transport, Search and Rescue and test pilots.

2.3 Procedure

Each pilot was interviewed at their place of work. In line with common practice using the CDM, each participant was asked to think of a critical incident they had been involved with, which was defined as being 'a non-routine or un-expected event that was highly challenging and involved a high workload in which you were the primary decision maker' (Klein and Armstrong 2005). Most of the participants were on duty at the time they were interviewed, therefore interview time could not be guaranteed and so the shortened version of the CDM was used; i.e. only the timeline construction and deepening probe phases were conducted. Each participant provided a high-level overview of the incident and structured a timeline of events. After the incident description/timeline construction phase, the cognitive probes were asked in relation to the decision-making made during the incident. This study was granted ethical permission by the University of Southampton Research Ethics Committee. The interviews were audio recorded and later transcribed.

2.4 Data analysis

The 20 CDM interviews produced data about critical incidents that were classified into five broad types of incident (see Table 2). The annual review by the European Aviation Safety Agency (2012) demonstrated that after loss of control incidents, system failure (electrical and non-electrical combined) was the highest cause of fatal and non-fatal accidents. This suggests that the breakdown of incident type demonstrated here is in line with official statistics, although, without a comprehensive comparison of incident records, we would not go as far to claim that the types are fully representative. The data from each interview were structured into six generic phases of incident that have been previously identified in similar data (Plant and Stanton 2012b). The six phases were (1) pre-incident, (2) onset of problem, (3) immediate actions, (4) decision-making, (5) subsequent actions and (6) incident containment. The data were analysed in accordance with guidelines on qualitative data analysis whereby the text was chunked into meaningful segments of approximately one sentence or less in length (Strauss and Corbin 1990). Across the 20 interviews, there were 584 text segments. These text segments were then subjected to deductive thematic analysis that involved classifying the data into meaningful themes generated from existing theory (Boyatzis 1998). The coding scheme was based on the three categories of the PCM and developed in line with Boyatis' (1998) five criteria of how to structure a meaningful code. The text segments were coded for instances of the themes identified in the coding scheme. This method has been previously applied before for accident reports (Plant and Stanton 2012a) and decision-making data (Plant and Stanton 2013b). The coding scheme is summarised in Table 3.

For each interview, data from each phase of the incident were collated into a frequency table that captured 'from–to' links between the three categories of schema, action and world and was recorded in a frequency count matrix table. For example, if a text segment coded as 'schema' was followed by a text segment coded as 'action', this was recorded as one in the schema–action cell in the matrix table. This was summed across the 20 interviews to create an amalgamated frequency count for each of the six phases and across the data-set as a whole. The raw data are presented in Table 4.

Table 2. Classifications of incident types that emerged from the CDM interviews.

Incident type	Description	No. of interviews
Technological failure or malfunction	The incident occurred as a result of a failing or malfunctioning technical system	10
Environmental conditions	The incident occurred due to poor weather conditions	4
Spurious warning/caution	The incident occurred as a result of the onset of a warning or caution light and alarm, without any other signs of a problem	3
Human error	The incident occurred as a result of human error, either on the part of the pilot or someone else	2
Operational incident	The incident occurred whilst on an operational exercise and was a direct result of an operational procedure	1

Table 3. PCM coding scheme (adapted from Plant and Stanton 2013b).

	Code name		
	Schema	Action	World
Definition	Mental structures held by individuals that organise their representations of the world	The process or statement of doing something, or the intention to do something	Externally available information in the world (environment)
Description (for coding)	Statements relating to the use of prior knowledge and experience, i.e. things based on experience, expectation or 'knowing' things (this could be implied information through the discussion of training and/or standard operating procedures)	Statements of doing an action or discussion about potential actions that could be taken	Statements relating to potential or actual information existing in the world (environment). These can be physical things, conditions or states of being.
Example	'my expectation was that the engine would take a while to start in the rain'	'I turned on the engine'	'Caution light came on'

2.5 Reliability of the coding scheme

The reliability of the PCM coding scheme was assessed to establish the inter-rater (different people coding the data) and intra-rater (same people at different times) reliability. This is an established method to analyse the quality of a coding scheme (Burla et al. 2008). To assess reliability, three additional coders were judged by the standard set by the expert coder in a blind condition, i.e. raters were unaware of the expert's coding decisions. The additional coders were trained on the theory behind the coding scheme and the classification categories, they were unfamiliar with the previous use of this coding scheme. The coders were presented with 200 text segments (10 from each interview) which represented 34% of the data. The text segments were selected using a random number generator. This randomly generated 10 numbers within the range of total number of text segments for each interview. Intra-rater reliability was assessed by the three coders coding the same data 3 weeks later. In addition, the original expert coder recoded the 200 selected text segments. This occurred 13 months after the original coding had taken place.

Reliability scores were calculated based on percentage agreement, i.e. number of agreements divided by the number of times the coding was possible, multiplied by 100. This was in accordance with the literature that has suggested this is the

Table 4. Amalgamated from/to link frequency count data from the twenty CDM interviews.

			To				
Phase			World	Schema	Action	Total text segments	% of data/phase
Pre-incident	From	World	–	5	21		
		Schema	2	–	2		
		Action	21	2	–	53	9%
Onset of problem	From	World	–	20	37		
		Schema	13	–	13		
		Action	37	11	–	131	23%
Immediate actions	From	World	–	15	31		
		Schema	6	–	39		
		Action	37	13	–	141	24%
Decision-making	From	World	–	14	30		
		Schema	7	–	34		
		Action	38	14	–	137	24%
Subsequent actions	From	World	–	10	26		
		Schema	9	–	9		
		Action	27	9	–	90	15%
Incident containment	From	World	–	2	11		
		Schema	2	–	6		
		Action	11	0	–	32	5%
Total	From	World	–	66	156		
		Schema	39	–	103		
		Action	171	49	–	584	100%

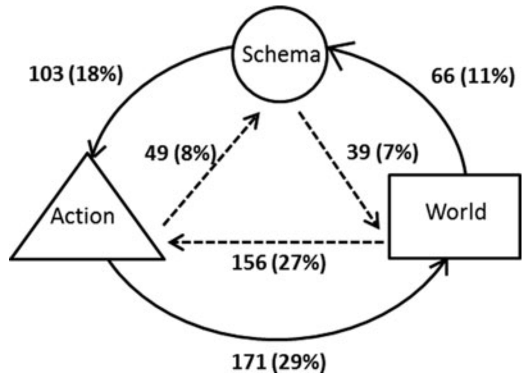

Figure 2. The PCM annotated with the number of from/to links (and percentages) for the amalgamated data ($n = 20$).

most suitable way to calculate reliability scores with data of this nature (Boyatzis 1998). There is general consensus that 80% agreement is the threshold for acceptable agreement (Lombard, Snyder-Duch, and Bracken 2002; Marques and McCall 2005) and this is used as the benchmark here for assessing reliability.

All results from the reliability assessment exceeded the 80% threshold level of agreement. Inter-rater reliability averaged 84% (ranging from 81% to 87%) and intra-rater reliability averaged 90% (three coders) and 97% (expert coder). A previous study with 20 additional coders also resulted in inter- and intra-rater reliability above the threshold of acceptable agreement and this was shown to be considerably higher than from chance alone (Plant and Stanton 2013b). These results suggest that the coding scheme will generate consistent results, whether it is used by different people or the same person on different occasions and can therefore be used with increased confidence.

3. Composite account of aeronautical decision-making

3.1 Whole incident

Figure 2 presents the PCM annotated with the number of from/to links (and percentages) from the amalgamated data of all of the incidents, over all of the phases. There are two possible ways that information can flow around the cycle: the traditional perceptual cycle (represented by the solid arrows around the outside of the model) and the counter-cycle (represented by the dashed arrows in the middle of the model). The traditional PCM accounts for 58% of the data, broken down as follows: 11% world–schema, 18% schema–action and 29% action–world. The counter-cycle accounts for 42% of the data, decomposed into 27% world–action, 8% action–schema and 7% schema–world. Table 5 presents this information by individual phase and will be discussed further in the following sections.

3.2 Incident phases

Table 4 displays the percentage breakdown of data across the six phases. The spread of data across the phases are as expected. The majority of the data are represented in the following three phases: onset of problem (23%), immediate actions (24%) and decision-making (24%). This is unsurprising given the nature of the interview in asking pilots to describe a

Table 5. Percentage of data associated with each branch of the traditional perceptual cycle and counter-cycle for each phase of the incident.

		Percentage of data in each phase of the incident					
		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Traditional perceptual cycle	Schema-action	4	10	28	25	10	20
	Action-world	40	28	26	28	30	34
	World–schema	8	15	11	10	11	6
	Total	52	53	65	63	51	60
Counter-cycle	World–action	40	28	22	22	29	34
	Action–schema	4	9	9	10	10	0
	Schema–world	4	10	4	5	10	6
	Total	48	47	35	37	49	40

critical incident and the associated actions and decisions. This is followed by subsequent actions (15%), pre-incident (9%) and incident containment (5%) phases. The pre-incident and incident containment phases provide context about what happened before and after the incident and are not directly related to dealing with the incident. Therefore, it is unsurprising that they contain the least data, some pilots started their descriptions in the onset of problem phase or concluded it in the subsequent action phase, hence the smaller amounts of data in these phases.

3.2.1 Phase 1: Pre-incident

The pre-incident phase contained 9% of the data. In this phase, pilots generally set the scene and described any antecedents to the incident, including the weather conditions (e.g. 'it was a reasonable day, strong breeze, not a gale just wind' CDM_018), the operational context (e.g. 'I was by myself going to pick up a client in Manchester' CDM_008) and any actions undertaken (e.g. 'I completed the pre-take off checks' CDM_018). Table 5 presents the percentage data (derived from the number of from/to links) from the amalgamated data of the pre-incident phase. Slightly more data flow around the traditional perceptual cycle (52%), compared with the counter-cycle (48%). The majority of data (80%) fall into a mini-cycle between world and action and back to work. This is unsurprising in the pre-incident phase where pilots described the context behind the incident and the initial piloting actions, therefore limited data are connected to the schema node; pilots were not drawing on past experiences or expectations as they were providing a descriptive, factual, account of the conditions. The counter-cycle is discussed in more detail in Section 4.2.

3.2.2 Phase 2: Onset of problem

Data in this phase described the critical incident (e.g. '*the instrument panel lights failed*' CDM_017, '*both the hydraulics systems started fluctuating . . . the whole aircraft started vibrating*' CDM_023, '*we basically flew into a waterfall, torrential downpour . . . we were in inadvertent IMC in terms of loss of visual references*' CDM_011). Table 5 presents the percentage data (derived from the number of from/to links) from the amalgamated data of the onset of problem phase. The traditional perceptual-cycle flow of information accounts for 53% of the data and the counter-cycle for 47% of the data. Again, the reciprocal mini-cycle between world–action–world–action is evident suggesting a heavier emphasis on bottom-up compared with top-down information processing. This is unsurprising given that pilots described the conditions of the incident (e.g. '*the amber caution light came on*' CDM_008) and relevant actions (e.g. '*I checked the temperature and pressure gauges*' CDM_008) in this phase. The schema, top-down, element is represented in this phase as pilots drew on past experience, either their direct or trained experience, to process what was going on (e.g. '*initial perception because of what we're trained is this was a double engine failure*' CDM_ 009).

3.2.3 Immediate actions

The onset of problem phase is followed by the immediate action phase and accounts for nearly a quarter (24%) of the overall data. Whilst actions are described throughout every phase of the incident, the immediate action phase incorporates text segments that specifically relate to actions (and associated world information and schema descriptions) to ensure the immediate safety of the flight. This is exemplified through an extract from CDM_020 [including the associated PCM codes]:

> '. . . the first thing to remember is to continue flying the aircraft [action] . . .
> . . . we were in a turn [world] . . .
> . . . so I get it back to a safe flying configuration, well within the bounds of one good engine [action] . . .
> . . . there are minimum speeds and power figures [world] . . .
> . . . which you just know through training [schema]'

The immediate action phase also encompasses data that described the pilot trying to identify what the problem was and this is exemplified through an extract from CDM_014:

> '. . . immediately scanned my instruments' [action] . . .
> . . . saw that everything was working, readings were all normal [world] . . .
> . . . interestingly enough I had a similar problem about a year earlier so I had a seed in my mind about what had happened [schema] . . . .
> . . . I shut down the engine in preparation for an auto-rotation [action]'

Table 5 presents the percentage data (derived from the number of from/to links) from the amalgamated data for the immediate action phase. In the immediate action phase, the majority of the data fall into the traditional perceptual cycle (65%), compared with 35% in the counter-cycle. Furthermore, compared with other phases, this phase is very top-down driven with 28% of data in the schema–action link. This phase is characterised by an iterative cycle of assimilating information in the world and drawing on past experiences, whether that is from training or direct experience, to produce the appropriate actions. The exert from CDM_014 presented earlier exemplifies this transition around the traditional PCM (action–world–schema–action).

3.2.4 Decision-making

The decision-making phase accounts for 24% of the total data. Decisions are made continuously throughout the incident, but this phase is characterised by text segments specifically relating to the overall decision made for dealing with the incident. Data for this phase generally came from the answer to the CDM probe: What was the primary decision that you made? Text segments in this category relate to the actions taken during this phase, the use of past experience and the environmental information that assisted the decision-making process. Therefore, all three elements of the PCM were represented in this phase, with the majority of the data falling into the traditional perceptual cycle (63%), compared with the counter-cycle (37%). Table 5 presents the percentage data (derived from the number of from/to links) from the amalgamated data for the decision-making phase. As with previous phases, within the counter-counter, the world–action link is strong, contributing to a reciprocal mini-cycle between world–action–world–action. The schema–action link accounts for a quarter of the data in this phase, suggesting a strong top-down information-processing component in the decision-making phase. This is unsurprising as many of the pilots drew on past experiences to assist their decision-making process, this ranged from direct past experience, e.g. ‘I’d had a similar incident . . . there was a bang, nowhere near as loud as this . . . but a little bit of vibration associated with it, which suggested to me it could be the same problem’ (CDM_014), past experience developed through training, e.g. ‘the decision of what to do was in my experience because of training, I had seen this instance before in a simulator’ (CDM_004), and vicarious past experience developed through reading or speaking about potential situations, e.g. ‘something did go through my mind, I had been talking to an instructor who asked me what I would do in a similar situation . . . ’ (CDM_006).

3.2.5 Subsequent actions

The subsequent action phase accounts for 15% of the overall data. This phase encompassed data relating to additional actions taken as a result of the decision-making phase. Generally, actions involved whether to land the aircraft immediately, land the aircraft as soon as possible or resolve the incident in the air. Table 5 presents the percentage data (derived from the number of from/to links) from the amalgamated data of the subsequent action phase. There is almost an even split between the two cycles; traditional perceptual cycle (51%) and the counter-cycle (49%). Within both cycles, the action–world (30%) and world–action (29%) links account for most of the data, suggesting that this phase is characterised by bottom-up information processing. This makes sense in a phase that focuses on the actions undertaken and the world information that is drawn upon to confirm the actions. For example:

> ‘ . . . I was scanning for a field in front’ [action] . . .
> . . . the field had to be somewhere in my field of view, not the best or ideal field but the best field directly in front of me in a mile range’ [world] . . .
> . . . I pointed my aircraft roughly at a set of fields . . . I was trying to reduce the speed [action] . . .
> . . . the dials were moving all over the place’ [world]’ (CDM_005)

3.2.6 Incident containment

The final phase of the incident is the incident containment phase. This phase only accounts for 5% of the overall data because it generally contained only a few text segments as pilots concluded their account of the incident. This phase is exemplified with the following text segments: ‘it was a normal shut down because the transmission had not yet seized’ (CDM_008), ‘landed and another aircraft landed next to me, engineer looked at it . . . ’ (CDM_014) and ‘I was talked in by a controller . . . I broke cloud at 200 feet and landed normally’ (CDM_006). Within this phase, the traditional perceptual cycle represents the majority of the data (60%), compared with the counter-cycle (40%), which is incomplete as the action–schema link is not represented (see Table 5).

4. Discussion

The aim of this study was to explore the validity of the PCM in order to establish whether data flow in the manner described by Neisser (1976). To undertake this analysis, 20 CDM interviews were conducted with rotary wing pilots about critical incidents they had been involved with. Each incident was structured into six key phases and the text segments within each phase were subjected to deductive thematic analysis. The data were amalgamated to produce composite PCMs of information flow for each of the incident phases and across the data-set as a whole. In exploring the validity of the PCM, this research also built upon a previous study by Plant and Stanton (2013b) in which the PCM was used as the basis for examining the process of aeronautical decision-making. Within this section, we also discuss the practical applications, evaluate the methodology employed and outline future research endeavours.

4.1 Validating the PCM

The principle of validity refers to whether a concept or theory corresponds to the phenomenon observed in the real world. In this case, whether the cycle of information processing in the perceptual cycle occurs as Neisser (1976) described it. The PCM suggests that information flows in a cyclical manner in which the environment (world information) informs the operator, modifying their knowledge (schema). These schemata direct the operator's activity (action) in the environment. These actions result in the sampling of the environment, which in turn informs the operator. Here, we sought to determine the construct validity of the PCM by conducting deductive thematic analysis on qualitative data obtained from 20 CDM interviews. Thematic analysis is the process of identifying, analysing and reporting patterns within data (Braun and Clarke 2006). This was deductive, or theoretically driven, because a classification scheme based on the three key elements of the PCM was used; schema, action and world, to analyse the critical incident data. Braun and Clarke (2006) advocated the use of deductive thematic analysis when coding for specific research questions, in this case, exploring the validity of the PCM. Braun and Clarke (2006) argued that the hallmarks of a quality thematic analysis include limited overlap between themes, all data should be able to be classified and all aspects of a theme should adhere to a central idea or concept. Here, the classification scheme resulted in exhaustive (i.e. all text segments were classified) and exclusive (i.e. there was no ambiguity about which code text segments should be assigned to) coding, achieving Braun and Clarke's (2006) principles of quality thematic analysis. This suggests that the PCM is effective at explaining critical decision-making and therefore supports the previous assertions made by Plant and Stanton (2013b) that the PCM is a useful framework from which to study the processes of (aeronautical) decision-making.

A frequency count of the from/to links was conducted on the text segments, as they appeared in the interview transcripts, for example, schema–action or world–action, etc. This was used to create composite perceptual cycles of each of the phases of the incident. The composite analysis demonstrates that, on the whole, the PCM explains the critical decision-making data. The traditional perceptual cycle in which information flows from world to schema to action and back to world accounted for 58% of the data. This demonstrates that the majority of data flow around the perceptual cycle in the way Neisser (1976) anticipated; however, there is a noteworthy proportion of the data that flow in the counter-cycle (42%), particularly in the world–action link. This results in a mini-cycle between world to action and then action back to world; this is discussed in detail in Section 4.2. Overall, the links that come from/to the schema node hold less data than the links related to the action and world nodes. This is potentially a product of the data collection method or the experience level of the participants and is accounted for in Section 4.4.

The traditional perceptual cycle flow of information is most evident in the immediate action (65%) and decision-making (63%) phases of the incident. The immediate action phase is characterised by an iterative cycle of assimilating information in the world and drawing on schemata, developed through training or direct experience, to produce appropriate actions. Similarly, in the decision-making phase, text segments related to actions taken, the use of past experience and the available environmental information that assisted the decision-making process. The analysis of 20 case studies has demonstrated that the perceptual cycle theory can explain the CDM data, exclusively and exhaustively. The rigour with which the analysis was conducted increases confidence with our conclusions, thus assuring the usage of the PCM as a theoretical foundation for applications such as accident analysis and decision-making modelling.

4.2 The counter-cycle and levels of behaviour

As described in the previous section, the traditional perceptual cycle was able to account for the majority of the critical incident data. However, it was also found that some of the data fitted into the counter-cycle, with information flowing in the opposite direction from the traditional world–schema–action cycle and instead flowing in a world–action–schema cycle. This counter-cycle accounted for 42% of the overall data, it was most evident in the subsequent action phase, accounting for 49% of the data. Within the counter-cycle, the majority of the data occurred in the world–action branch. In the traditional PCM, the world is only connected to action by schemata. An equal amount of data was often found in both the world–action branch and the action–world branch. Initially, when analysing the data from each incident, a flow analysis was conducted in which the from/to links were recorded around the PCM in the order in which they occurred. The main point taken from this flow analysis is that a reciprocal mini-cycle often occurred between the world and action nodes, and this is exemplified in the following with data from CDM_019:

'We launched from the pick-up site . . . ' [action]
'The cloud was still lowering' [world]
' . . . given the high risk I thought I would head to the top of the cloud, so we climbed 4500ft and zoomed over on clear sky' [action],
'Now we were over the destination, there was no gap in the cloud' [world],
'We were going around in circles' [action]
'I had maps but there was no radar' [world]
'I was trying to calculate how much clearance I had' [action]

Rasmussen's (1983) skill-, rule- and knowledge-based behaviour taxonomy (SRK) can help explain this. SRK describes three different levels of cognitive control that can be exercised by an individual over their actions. Skill-based behaviour (SBB) refers to the smooth execution of highly practised, physical actions where there is virtually no conscious monitoring. Klein, Calderwood, and Macgregor (1989) described this automaticity as 'recognition primed'. At this level, recognition of certain patterns (world information) maps directly onto the selection of an appropriate response (action). SBB develops through extensive practice in which operators acquire cued response patterns suited for specific situations. In the from/to link analysis, SBB manifests as direct links from world information to actions (as exemplified earlier). For skilled pilots, in familiar aircraft and environments, the action of flying the aircraft is executed largely without effortful thought, hence the schema node is bypassed as information from the environment is automatically assimilated and appropriate actions are performed (Rasmussen 1974).

Neisser's (1976) original PCM distinguished between top-down and bottom-up information processing. The former being schema-driven processing around the left-hand side of the PCM, and the latter being environmentally driven information processing depicted on the right-hand side of the model. To generate appropriate responses to novel situations, an operator needs to integrate more general knowledge concerning the behaviour of the system, the characteristics of the environment and the goals to be achieved (Drivalou and Marmaras 2009). In the PCM, this manifests as the top-down flow of information processing, whereby actions are driven by stored schemata and the resulting change on world information is monitored. This knowledge-based behaviour (KBB) requires considerable feedback and this is accounted for in the PCM by the modifying effect that world information can have on the future utilisation of schemata. In the data analysis, the schema node is the least represented with less from/to links when compared with the action and world nodes. The participants in this study were experts in the sense that, based on flying hours, they were experienced aviators. By its definition, a schema is a mental template developed through past experiences and associated expectations (Bartlett 1932). As such, experts have more past experiences and therefore a wider repertoire of schema to draw upon. It could therefore be hypothesised that the schema links should be highly represented in the data because the expert pilots utilise their stored schemata to deal with the incidents. However, when viewed from the perspective of the SRK taxonomy, it is more likely that the expert pilots engage in automatic SBB, rather than the effortful KBB. Furthermore, in automatic routines SBB may continue to control behaviour, even when higher level processing becomes necessary so that a person engaged in RBB or KBB could still be engaged in actions under skill-based control (Hobbs and Williamson 2002).

Hobbs and Williamson (2002) have argued that the SRK taxonomy has begun to acquire status as an 'industry standard' in a variety of settings. However, the SRK taxonomy only focuses on the mind of the individual, i.e. the level of cognitive control that is implemented, and it does not acknowledge the role of the environment in shaping and modifying operators' behaviour. The fact that the PCM acknowledges the interaction between an operator and their environment is a significant strength of the model. Furthermore, it aligns the PCM with the Cognitive Systems Engineering (CSE) approach (Hollnagel and Woods 1983; Hollnagel 2001), which is a relatively recent branch of the ergonomics discipline. CSE views the unit of analysis as the whole system, i.e. the human–machine interaction, rather than just the decomposition of both the human and the system as separate entities, something clearly echoed in the PCM (see Plant and Stanton 2013a for a more detailed discussion of the role of the PCM in CSE). Plant and Stanton (2014) have previously justified the use of the PCM to explore decision-making processes over the more popular recognition-primed decision (RPD) model (Klein 1999) because the RPD model does not capture the cyclical interaction between an operator and their environment as successfully as the PCM does. As such, the explanatory power and potential utility of the PCM (and in turn the SRK taxonomy or the RPD model) can increase if they can be aligned together as each capture elements that the others do not.

4.3 Practical applications

At the start of this paper, we argued that it is essential to establish the validity of models and theories so they can be used with confidence (Stanton and Young 1998; Salmon et al. 2009b). This is especially pertinent with the PCM as it has been extensively applied and used for accident analyses where first-hand accounts are often unavailable (e.g. Plant and Stanton

2012a; Salmon et al. 2013). The results of this study have demonstrated that the PCM does uphold the principles of construct validity and as such it can continue to be used with increased confidence. Interestingly, our findings also demonstrated the occurrence of a counter-cycle within the original model, which needs to be accounted for if the PCM is used as a framework for data analysis. The results presented here have offered an extension to Neisser's original work and whilst the research context is aeronautical decision-making, it can be argued that aviation epitomises the NDM environment in complex sociotechnical systems. The findings can generalise to other complex human–machine systems, either in other transport domains, control process domains and other safety-critical systems.

As previously argued by Plant and Stanton (2012a, 2013b), to further our understanding of decision-making, it is essential to understand why actions and assessments of operators made sense at the time they were made within the context of local rationality (Dekker 2011). When investigating incidents or accidents, rather than jumping to the human error conclusion, which is so often the case, the PCM provides a framework to consider the systemic process of decision-making. The incorporation of both internal schemata and external context into the PCM allows this understanding to occur; however, this is usually in the form of retrospective accident analysis (e.g. Stanton and Walker 2011; Plant and Stanton 2012a; Salmon et al. 2013). Maurino (2000) has challenged the aviation industry to produce more proactive, rather than reactive, safety research. The PCM approach goes towards what Maurino (2000) termed a contemporary approach to safety because it proposes errors as symptoms rather than causes of safety breakdowns, because error-inducing factors are latent in the context, i.e. the environmental conditions that, through their interaction with cognitive schemata, influence actions and perception.

O'Hare (1992; O'Hare, Mullen, and Arnold 2010) argued that decision-making performance is not a function of factual knowledge and that alone, a repertoire of perceptual-motor skills and formal rules, is insufficient to become a fully proficient pilot. In aviation, or other system management environments, experts possess the ability to compare current situations with previously experienced situations. The role of schemata is captured by the PCM, and from the excerpts provided in Section 3, it is clear that pilots utilised a variety of schemata including those developed through direct past experience, trained past experience and vicarious past experience. The PCM therefore has the potential to be a framework for training aids centred on decision-making. Within the aviation domain, the importance of case-based reflection is well established as a means of enhancing aeronautical decision-making. For example, Henley, Anderson, and Wiggins (1999) advocated the use of reflective journals as effective means of accelerating the development of an experiential knowledge base from which to make decisions and judgements. Similarly, O'Hare, Mullen, and Arnold (2010) found that participants who reflected on a set of cases involving pilots flying into adverse weather conditions were more likely to follow weather-related flight rules in a simulated flight than participants who completed a free recall task. The PCM framework could potentially be utilised as a way to structure reflective decision aids or decision-making training modules. This research has demonstrated that pilots engage in the PCM when dealing with critical incidents. Therefore, if pilots are taught the principles of the PCM and the interaction between the elements, there is the potential for higher retention rates if reflection and/or training is aligned with the information-processing mechanism pilots are actually utilising.

4.4 Evaluation of methodology and future research endeavours

Some of the methodological considerations with research of this nature have already been acknowledged and they will be further discussed in this section. In relation to the data collection method, the CDM is open to criticism. Of the three elements of the PCM, schemata are the hardest to elicit and measure. They are mental constructs and are therefore not open to direct observable measurement and are not necessarily as consciously recalled as world information might be (Plant and Stanton 2013a). The justification for selecting the CDM was well considered and provided in Section 2.1; however, there is still a potential for bias in the data (e.g. text segments to relate to world and action rather than schema). We have previously discussed this in light of the SRK behaviour taxonomy, and it might be that schemata were not elicited by the CDM because of the expertise of the participant group. An alternative explanation is that the CDM method is not sophisticated enough to elicit schema-based data and the results were partly a product of the data collection method. This can only be resolved through comparing and contrasting different data collection techniques. Annett (2002) argued that data collection is always open to some form of bias. Furthermore, specifically in relation to mental models, Revell and Stanton (2012) showed that bias varies considerably depending on the theoretical perspective used and methods of data capture and argued that as long as biases were acknowledged, findings could be trusted. Fundamentally, we are confident that the results are a product of real phenomenon and not the data collection method, although it is a potential issue that warrants acknowledgement.

In relation to the data analysis method, Braun and Clarke (2006) have warned that because deductive thematic analysis is driven by the researcher's theoretical interests, it is more explicitly analyst driven and potentially more subjective than inductive analysis in which themes emerge from the data-set. As such, a reliability assessment was undertaken to establish the inter- and intra-rater reliability of the coding scheme. The results demonstrated inter-rater reliability of 84% agreement and intra-rater reliability of 97% agreement, increasing confidence in the use of the coding scheme. Furthermore, the generation of a coding scheme based on existing theory is arguably more objective than generating themes from data as they emerge. Here, all possible measures were taken to optimise the objectivity of the analysis: the coding scheme was developed in line with Boyatzis' (1998) five criteria for how to structure a meaningful code, a systematic analysis procedure was implemented that followed the guidelines provided by Braun and Clarke (2006) and an assessment of reliability was conducted.

In their overview of the advantages of the deductive thematic analysis method, Braun and Clarke (2006) argued that the approach can usefully summarise key features of a large body of data and can generate unanticipated insights. This was clearly evident in this study as the data analysis uncovered the counter–cycle, and the mini-cycle, occurring between elements of the PCM there were previously unlinked. This has led to questions about the nature of engagement in the perceptual cycle between novices and experts. A further avenue of future research is to delve deeper into the nature of the three PCM categories. Throughout this article, we have alluded to different categories within each of the PCM elements. For example, in Section 3 we referenced different types of world information, including natural environment, operational context and location; different types of schemata, including direct past experience, vicarious past experience and trained past experience; and different types of actions were evident in the transcripts, including aviating, navigating and communicating. Currently, the PCM categorisation provides a high-level over view of what is going on, but it would be useful to explore the detail in each category to establish the types involved and explore differences, be that in terms of incidents, pilot experience or domains of application.

5. Conclusion

This article sought to explore the validity of the PCM and, in doing so, built on previous research supporting the use of the PCM as a framework for understanding, modelling and explaining decision-making processes. To our knowledge, this is the first attempt to establish the validity of a widely used model and the motivation for such research is to ensure the model can continue to be used with confidence, although more studies of this nature need to be undertaken in a wide variety of domains. A model or theory can be considered valid if, after careful scrutiny, no objection or contradiction can be sustained. This research has demonstrated that on the whole the PCM provides an accurate representation of information processing when dealing with critical incidents. However, the counter-cycle that was observed suggests that experts might process information in a slightly different way and this warrants future investigation and provides a new development for the theory.

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