Development of a novel hybrid cognitive model validation framework for implementation under COVID-19 restrictions

Paul B. Stone | Hailey Marie Nelson | Mary E. Fendley | Subhashini Ganapathy

Department of Biomedical, Industrial, and Human Factors Engineering, Wright State University, Dayton, Ohio, USA

Abstract

The purpose of this study was to develop a method for validation of cognitive models consistent with the remote working situation arising from COVID-19 restrictions in place in Spring 2020. We propose a framework for structuring validation tasks and applying a scoring system to determine initial model validity. We infer an objective validity level for cognitive models requiring no in-person observations, and minimal reliance on remote usability and observational studies. This approach has been derived from the necessity of the COVID-19 response, however, we believe this approach can lower costs and reduce timelines to initial validation in post-Covid-19 studies, enabling faster progress in the development of cognitive engineering systems. A three-stage hybrid validation framework was developed based on existing validation methods and was adapted to enable compliance with the specific limitations derived from COVID-19 response restrictions. This validation method includes elements of argument-based validation combined with a cognitive walkthrough analysis, and reflexivity assessments. We conducted a case study of the proposed framework on a developmental cognitive model of cardiovascular surgery to demonstrate application of a real-world validation task. This framework can be easily and quickly implemented by a small research team and provides a structured validation method to increase confidence in assumptions as well as to provide evidence to support validity claims in the early stages of model development.

KEYWORDS

cardiovascular surgery, cognitive modeling, COVID-19, model validation, validation frameworks

1 | INTRODUCTION

The recent outbreak of COVID-19 (SARS-CoV-2) at the beginning of 2020, has caused 49.7 million individuals to become infected and caused 1.2 million fatalities globally as of November 2020 (World Health Organization, 2020). The outbreak has prompted government intervention through widespread shutdown of nonessential businesses and services, implementation of social distancing guidance, and reallocation of resources and funds to better assist with viral mitigation and containment efforts (Ashraf, 2020). In addition to social and institutional shutdowns, economic downturn has also ensued due to loss of funding, lack of consumer spending, and uncertainty around the return to pre-COVID-19 normalcy. The ramifications have not only impacted the global economy but have also had a significant effect on the research community within public and private institutions (Ashraf, 2020). The American Journal of Emergency Medicine has outlined specific focus areas and guidelines for research during the COVID-19
pandemic (Haleem et al., 2020). Personal Protective Equipment has been redistributed to those fighting the virus on the frontlines, participants and researchers have been prohibited from participating in in-person research (unless pertaining directly to COVID-19) and reassigned to staggered schedules or remote work to reduce the amount of face-to-face interaction and to maintain appropriate social distancing guidelines. Pertinent research in the healthcare field has also been largely suspended as an attempt to allocate the most physical and financial resources possible to fighting the virus and predicting future viral outcomes.

The face-to-face work of human factors researchers has been affected particularly hard by these restrictions, as this historically requires extensive human interaction to elicit information regarding cognitive and decision-making processes (Sy et al., 2020). Much of this work requires structured in-person studies to be conducted utilizing observational and probing techniques. Given that many current studies in Human Factors research are not related to battling COVID-19, they are not considered essential practices. In the case of healthcare, this problem is compounded as subject matter experts (SMEs), especially those on the frontlines, are not readily available to participate in related studies, and non-essential research personnel are restricted from healthcare facilities, necessitating that test and evaluation procedures are moved online or remote (Sy et al., 2020).

Alongside these negative impacts, there is an opportunity to develop new and innovative tools and capabilities for remote implementation of human factors methods. Cognitive model development is an area of human factors research that is heavily reliant on face-to-face communication, both to develop models and perform validation and assessment studies. We believe there is a clear need for methods that allow the development and validation of cognitive models without reliance on in-person observations and face-to-face interviews.

Cognitive models are widely used in psychology and cognitive engineering to understand where errors are made or how training systems can be developed to reinforce a user’s cognitive model. They are a means for researchers to understand, describe and predict how individuals or teams perform cognitive tasks, such as information processing and decision making, and can highlight relevant cognitive states and actions (Rupp & Leighton, 2016). Wagenaar et al. (1990) suggest that there are specific errors associated with specific cognitive states, and that knowledge of the cognitive model can be used to reduce errors and improve decision making.

Hayes-Roth and Hayes-Roth (1979) developed a cognitive model to understand the nature of the planning activity from apparently rational to apparently chaotic decisions made when individuals develop plans. The model allows the researcher to abstract types of knowledge and decisions made in planning to parse top level thinking and enable simulation of the underlying process. Similarly, the recognition-primed decision (RPD) model (Klein, 1993) examines the more abstract concept of naturalistic decision making. This model allows the researcher to relate outcomes of testing to more intuitive decision types which in turn can be used to confirm or reject an assertion about the decision-making being employed.

The application of cognitive models is addressed by Belkin (1984), who concludes that it is vital to understand the user’s problem to build a cognitive model. This explicit representation allows researchers to use computational techniques to quantify human cognitive performance through simulation (Cooper et al., 1996). For cognitive modelling to deliver its full potential benefit, it is important to ensure sound methodological principles are used to ensure output is repeatable and models produce valid predictions. There is a need for evidence in simulation and ergonomics science and studies of validity can provide this, giving additional credibility to the associated models (David, 2013; Stanton, 2016). Validation can improve confidence in the methods used by human factors engineers and is an important step in the modeling of a system (Annett, 2002; Stanton & Young, 1999; Stanton, 2016). We considered the questions asked by Landry et al. (1983) in determining our approach to validation: what does it mean for a model to be valid? and, does validity refer to the output, structure, or modelling process? Annett (2002) argues that, in ergonomic models in particular, it is essential to the validity of a model to ensure that the performance is consistent and predictive in nature. It is important to note that cognitive models can be complex in nature and a validation method that works for one model, may not work for another (Strube, 2001).

Keehner et al. (2017) discuss the general approach to validation of cognitive models, highlighting the requirement for an iterative, staged process. The goal of any validation method should be to support claims and validity arguments about the specific models to which it is applied (Keehner et al., 2017). Similarly, Kane (2013) argues that validation is an ongoing and iterative process, and we believe a structured validation framework could have utility in the early stages of research where gathering appropriate resources is difficult or not cost-effective. In this study we use the definition of validation as determining if the real system is represented by the model (Law, 1991). This is achieved by mapping the system capabilities with the model representation. More robust, quantitative validation procedures may be required as models are developed, but here we seek to determine if the model meets the basic requirements of representing the underlying cognitive processes.

For this study, the safety-critical nature of cardiovascular surgery makes validation key to future implementation of this proposed model and heightens the need to find alternative means of cognitive model validation to enable progress under COVID-19 restrictions. This paper attempts to address the question—how can we validate a cognitive model in the age of COVID-19 and remote testing? We outline a streamlined validation process and explain how we adapted existing thinking while developing an understanding of the evolving COVID-19 situation and innovated new approaches to cognitive model validation.

2 | AIMS AND OBJECTIVES

We aim to advance a simple, structured framework for cognitive model validation requiring no direct contact and minimal reliance on remote usability and observational studies. While this has been born
out of the necessity of the COVID-19 response, we believe a hybrid validation framework for cognitive modeling can have broader application to support cognitive systems engineering. We believe this approach can lower costs and reduce timelines to initial validation and could allow identification of problems early in model development, potentially preventing problems further downstream. Our case study focuses on the validation of a cognitive model of cardiovascular surgery, given restrictions associated with COVID-19.

2.1 | Scope

The intended output of this study is a Hybrid Cognitive Validation Framework to provide human factors researchers a means to expedite initial validation with minimal resources. We propose a validation process based on analysis of existing literature, reflexivity cross check, and cognitive walkthrough within the research team. A case study implementation of the validation framework is presented to demonstrate application and provide example output from the framework. This analysis was contingent on the availability of a candidate cognitive model developed before the COVID-19 restrictions. Although these restrictions may impact the development of cognitive models, this study focuses exclusively on the validation of cognitive models in this context. The scoring system used in this study is only preliminary for framework confirmation through implementation of the framework and associated feedback on scoring usefulness and accuracy.

3 | DEVELOPMENT AND TEST IMPLEMENTATION OF VALIDATION FRAMEWORK

In line with the aims and objectives of this study, we used the following process to develop and conduct a test implementation of the Hybrid Cognitive Validation Framework.

3.1 | Formalization of restrictions

COVID-19 restrictions are not uniform among countries, states and even cities and localities (Hale et al., 2020). As authorities balance the need for public safety with the desire to maintain economic activity, these regulations also vary over time. We, therefore, define specific conditions with which this validation framework is compatible. In addition to representing COVID-19 restrictions, these conditions also represent future situations under which the Hybrid Cognitive Validation Framework can be an effective tool for research teams. The restrictions used in this study are:

- No requirement for in-person intra-team meetings.
- No in-person contact with external SMEs during the validation process.
- Communication with SMEs is limited to confirmatory questioning—no probing or enhanced analysis due to assumed lack of availability.
- The research team has access to validation resources, such as those available online.

These restrictions are in line with initial COVID-19 restrictions implemented by the state of Ohio during the initial phase of the COVID-19 response (DeWine et al., 2020).

3.2 | Analysis of existing validation techniques

APA technical recommendations for psychometric tests defines the following four types of validity—Concurrent Validity, Predictive Validity, Construct Validity and Content Validity (American Psychological Association, 1954). Predictive and Concurrent methods are considered together as criterion validity and refer to the ability of a test to accurately predict, either in advance or concurrently, a predetermined measure or characteristic (Cronbach & Meehl, 1955). By contrast, Construct Validity (American Psychological Association, 1954) aims to determine if a test measures the underlying concept it aims to address (Middleton, 2019). Finally, there is Content Validity, which is established by demonstrating that test subjects are representative of the population of interest (Cronbach & Meehl, 1955). In this paper, we concentrate on construct and content validity, ensuring the model and its inputs are representative, rather than comparison of model outputs to known standards. These measures relate to the internal validity of the model and given the potential complexity of assessment, we do not focus on the external validity.

Before COVID-19 restrictions, the proposed validation procedure for the Cognitive Model of Cardiovascular Surgery, was to implement a method used by Craig et al. (2012) to validate a cognitive model of laparoscopic surgery. This method includes three validation stages, including data collection through SME interviews, construct encoding and comparison, and reflexivity phases including reassessment by additional participants who did not take part in the initial assessment. This is a modified version of an evidence collection and model validation developed in the knowledge audit method (Militello & Hutton, 1998). The process required multiple data elicitation procedures and cross comparison with SMEs with explicit procedures aimed at minimizing researcher bias.

The restrictions adopted in this study exclude face-to-face, concurrently gathered validity measures, and drive us toward remote, asynchronous measures, which, although easier to collect are somewhat harder to infer target cognitive processes from (Embretson, 1983). We considered several approaches to establish construct and content validity for the HCOG framework. Thoroman et al. (2019) use interview data as a reference standard to evaluate the validity of a near-miss reporting form. In this study, we adopt a similar approach, utilizing the cognitive walkthrough as our interview reference standard for empirical validity.
assessment of the HCOG model. Silva et al. (2020) validate a Descriptive Cognitive Model for predicting performance in Low-Code Development platforms. In this study, the model validation is achieved by comparison of knowledge-based and systems-based descriptions and by analysis of the model against specific tasks, appropriate to the Low-Code Development Platform. Stanton and Baber (2005) validate the Task Analysis for Error Identification, demonstrating improved performance compared with Heuristic evaluation, an approach developed by Stanton and Stevenage (1998). This method showed good reliability and concurrent validity for the Task Analysis for Error Identification technique. Cornelissen et al. (2014) consider the validation of a formative method, concentrating on cognitive work analysis, noting the importance of pooling results of multiple analysts in establishing validity. This reinforces the importance of the requirement for multiple researchers to conduct our validation framework.

Vinod et al. (2016) utilize Markovian modelling to represent humans and build task simulations to compare outcomes with potential human action. This was initially considered a strong option to provide objective, quantitative basis for evidence generation in the Hybrid Cognitive Validation Framework, however, the complexities of this approach and expert nature of surgeons meant this approach was discounted.

The argument-based approach to validation (Kane, 2013) aims to minimize complexity in the validation process while still evaluating claims and providing evidence to support them. The argument-based approach is based on early construct validity models (Cronbach & Meehl, 1955) which details three general principles for validity:

- The focus of the validation is on the interpretation of the output rather than the output itself.
- Validation is part of an ongoing research program.
- The proposed interpretation of the output is subject to critical evaluation.

The argument-based validation framework (Kane, 2006, 2013) also requires two argument types to support validity: An interpretive/use argument (IUA) and a validity argument. The IUA argument specifies the claims that are to be evaluated in the validation, while the validity argument is used to evaluate the interpretation of validation scoring. The argument-based method claims if these arguments are clear, coherent, and complete, and the inferences reasonable and assumptions plausible, a model can be said to be valid. We will use these definitions as the basis for the argument-based elements of our validation framework.

The cognitive walkthrough is a structured review method for conducting usability assessments early in the design cycle of a product (Lewis et al., 1990). It involves the generation of task scenarios and explicit assumptions regarding the user population and context of use. This method was initially developed to assess the usability design performance of user interfaces, but we believe it can be adapted to establish construct validity of models. The method requires definition of the user along with sample tasks or scenarios and action sequences that are compared with an implementation of the user interface (Lewis et al., 1990). In adapting this method to the validation of cognitive models, we establish sample tasks and incorporate these into credible vignettes or scenarios based on the implementation associated with the cognitive model. We ask the reviewer to determine if the cognitive paths and states in the model are representative of the decisions associated with the tasks in example scenarios, and to walkthrough the scenario, task-by-task and compare to the cognitive model of cardiovascular surgery.

The intended use of the model of cardiovascular surgery is to predict the surgeon’s workload through indirect assessment of cognitive state, linking the paths taken through the model to periods in a procedure where workload is high or low. Ideally, a method to evaluate concurrent validity of the prediction made by the model would be implemented, but given the restrictions due to COVID-19, this is not possible. We are aiming to demonstrate construct validity and content validity. Specifically, we aim to establish the ability of the model to represent the underlying concept (construct validity) and the representativeness of the model to the target population, in this case cardiovascular surgeons. For the purposes of this study, we utilize existing Cognitive Models in the decision ladder and RPD model. These models have been widely used and are subject to validation (Lintern, 2010; Rasmussen, 1974; Soh, 2007). Rather than focus on internal validation of the model structure, this study focuses on developing a validation approach to answer the question “Is a specific model representative of the cognitive tasks for which it is built?” We, therefore, propose a concept for a hybrid cognitive walkthrough (Lewis et al., 1990), argument-based validation method (Kane, 2006) to establish construct validity, augmented with reflexivity analysis (Davies & Dodd, 2002) to establish content validity. We believe including both the walkthrough analysis and argument-based methods provides a broad but flexible and adaptable basis for the validation of cognitive models that integrates into early iterations of model development and can be used to derive requirements for more complex assessments as well as providing evidence for model validity.

### 3.3 Define hybrid cognitive validation framework

This concept was developed into a specific validation framework detailing specific tasks to establish both construct and content validity. The tasks are representative of those in the donor validation methods, highlighting surrogate tasks where the restrictions of this study limited the scope of initial application. The expected outputs and interpretations are also defined.

### 3.4 Test implementation of the validation framework

The resultant framework was implemented in a case-study validation of a cognitive model of cardiovascular surgery. This wider context of the development of this cognitive model is development of a decision support system (DSS) to improve performance and reduce risk in cardiovascular surgery. Woods (1985) proposes that integrating
machine and human cognitive systems is the key to the application of such a DSS and that considering DSS as a unified Joint Cognitive System, as opposed to a stand-alone machine-based system, enables enhanced understanding of the goals and responsibilities of the system.

4 | HYBRID COGNITIVE VALIDATION FRAMEWORK

The Hybrid Cognitive Validation Framework consists of three core tasks, applied using an associated use case to illustrate the context for wider implementation. The three core tasks are: (1) Define objective and Interpretation framework (argument-based method), (2) Walkthrough analysis (3) Reflexivity analysis.

Task 1 is closely aligned to the two-stage argument-based validation method (Kane, 2013). The IUA task (Task 1A), requires the definition of a specific validation question and a definition of the purpose and scope of the validation framework implementation. The Validity task (Task 1B) requires the definition of specific interpretations of model validity assessment. These tasks should be conducted before implementing the remaining tasks within the validation framework implementation to prevent bias or fitting interpretations to align with results of the later analyses. Task 2 is the cognitive walkthrough validation method. This is aimed at confirming the cognitive paths and states within the model align with specific, credible cardiovascular surgery scenarios, by comparing defined tasks with the cognitive paths and states in the model. This method was developed to enable implementation without the need for face-to-face contact. This lack of direct exposure of SMEs to a cognitive model walkthrough is a key limitation of the Hybrid Cognitive Validation framework; however, our walkthrough analysis approach consists of two stages. Firstly, Task 2A, scenario development, where detailed vignettes of representative situations are generated. Multiple scenarios should be developed to provide greater variation of cognitive states and pathways to ensure robust validation of the cognitive model. Second, a walkthrough stage where Subject-Matter Experts utilize these vignettes, with reference to the cognitive model to determine how representative the states and pathways compare to the vignette requirement. Rather than require SMEs to record outcomes at each decision point and attempting to encode potentially incomplete or inaccurate data, we propose a four-level qualitative scoring system to enable a simplified assessment. Task 3 is an implementation of the Reflexivity analysis (Davies & Dodd, 2002). This stage aims to ensure model validation procedures and assessments are supported by suitable evidence and that SMEs used are qualified and documented. Clarity, coherence, and completeness are key to all tasks in this framework, in line with requirements defined by Kane (2013). The resultant Hybrid Cognitive Validation Framework is detailed in Table 1.

The reviewers identified to conduct the cognitive walkthrough are provided with the following instructions on the implementation of the method:

- Conduct a task-by-task walkthrough of the validation scenario (Tables 2 and 3) with reference to the cognitive task matrix (Table 4).
- For each task identified in the walkthrough scenario, record the paths taken through the cognitive model and identify where decisions and cognitive states and paths do not match.

These instructions are designed to be sent electronically and can be followed up with a discussion with the reviewer to clarify any elements of the walkthrough task. The research team can then utilize the results of the walkthrough analysis, in conjunction with the validation interpretation framework (Table 5) to assign validity scores to the model. This is an initial implementation of the walkthrough analysis method to support cognitive model validation and it is expected that the guidance for reviewers will be expanded based on the feedback received during this study.

4.1 | Validation framework implementation and scoring

The Hybrid Cognitive Validation Framework (Table 1) should be used as part of an iterative, scalable validation process with tasks completed sequentially. The model development stage is not scored but is included to indicate the chronology of the development within the validation process.

The argument-based analysis, walkthrough analysis, and reflexivity analysis tasks, detailed in Table 1, each have two sub-tasks with a potential for 5 points. The success criteria, or Validation (V) element scores (0–3 points) are summed with the objectivity (O) scores (0–2 points) to give an overall Validation Framework (VF) score (0–5 points). This gives a potential score of 5 points for each of the six tasks and sub-tasks and a total of 30 points for each implementation of the validation framework, with 18 points attributable to validation success criteria and 12 points to objectivity scoring. The inferences derived from this scoring are variable, dependent on the validation task, defined in the argument-based validation task (Kane, 2013). For a model to be considered “Good,” some objectivity analysis should be undertaken. For this reason, the threshold for “good” should be above 18 out of 30, hence even if the model achieves a score of 18/18 on the validation criteria element, the interpretation threshold should require a score above this to ensure that some objectivity analysis is completed.
TABLE 1  Hybrid cognitive validation framework

| ID | Sub Task  | Qualitative Validation Criteria | Objectivity (Reflexivity) | Overall Score/Evidence |
|----|-----------|--------------------------------|---------------------------|------------------------|
|    | (including responsibility) | Individual score (0–3 pts) | Individual score (0–2 pts) | Task Score (/10) |
|    | Task definition | Total task score (6 pts) | Total task score (4 pts) | Framework (/30) |
|    |            | Framework score (/18 pts) | Framework score (/12 pts) | |

**Task 1 Define the Validation Assessment Objective and Interpretation Framework (Argument-Based Method)**

**T1A IUA Task**

(Research Team)

The validation task is clearly stated and in line with the limitations of the framework. (+3 if true)

Validation objective clarity and coherence with interpretations assessed by second researcher. (+2 if true)

Written confirmation of assessment. (Total/5)

**T1B Validity Argument Task**

(Research Team)

Inferences are reasonable, assumptions are plausible and underpinning descriptions and evidence are clear, coherent, and complete. (+3 if true)

Validation objective clarity and coherence with interpretations assessed by second researcher. (+2 if true)

Written confirmation of assessment. (Total/5)

**TASK 2—Walkthrough Analysis Generate Scenarios, test matrix. Conduct cognitive walkthrough.**

**T2A Scenario Development Task**

(Research Team)

Scenario Assessment

(Subject Matter Expert)

Scenarios confirmed by second researcher. (+1 if true)

Detail scenarios used in the validation.

Provide Cognitive Task Matrix. (Total/5)

Generate scenarios that are representative of model use cases to enable cognitive walkthrough.

Scenarios are representative of operational situations (routine, emergency, complications). (+1 if true)

(Continues)
| ID | Sub Task | Qualitative Validation Criteria | Objectivity (Reflexivity) | Overall Score/Evidence |
|----|----------|--------------------------------|---------------------------|------------------------|
|    |          | There are significant gaps in the representation of cognitive states and pathways for many tasks. (0 pts) | (0 pts) | (0) if true |
|    | SME to Conduct cognitive walkthrough. | The model meets the basic requirements of representing the underlying cognitive processes but may have some gaps. (1 pt) | (1 pt) | (+1 if true) |
|    | - Qualitative Task 1 (Subject Matter Expert) | Cognitive states, actions, and pathways were clear, complete, and coherent and representative of all surgical phases in one scenario. (2 pts) | (2 pts) | (+2 if true) |
|    | TASK 3: Reflexivity assessment: Determine if appropriate data was collected to support model development? | Subjects(s) has/have no experience or expertise in the field. (0 pts) | (0 pts) | (0) if true |
|    | T3A | Subjects(s) has/have some training and minimal experience—less than 2 years. (1 pt) | (1 pt) | (+1 if true) |
|    | T3B | Data collection conditions were consistent across all participants. (1 pt) | (1 pt) | (+1 if true) |
|    | Cross-check qualifications | Data collection covered the breadth and depth of the model and a representation can be made. (1 pt) | (1 pt) | (+1 if true) |
|    | (Research Team) | The debrief was conducted by a second researcher, not present in the data collection. (1 pt) | (1 pt) | (+1 if true) |
|    | Were appropriately qualified subjects used in the model development? | Relevant data collection was used without omission or bias. (1 pt) | (1 pt) | (+1 if true) |
|    | Subjects(s) has/have some training and minimal experience—less than 2 years. (1 pt) | Subjects(s) is/are considered expert(s) and currently practicing—more than 5 years. (3 pts) | (3 pts) | (+3 if true) |
|    | Subjects(s) is/are experienced practitioner(s) and currently practicing—2–5 years. (2 pts) | | | |
5 | COGNITIVE MODEL FOR CASE STUDY

A generic cognitive model of cardiovascular surgery was developed with cardiovascular surgeons from the Miami Valley Hospital, Dayton, OH using a Cognitive Task Analysis method (Craig et al., 2012), along with unstructured interviews and cognitive walkthrough. Rather than develop a new model from scratch, existing cognitive models were considered to represent different phases in surgery with the aim of developing a more robust model with existing evidence. This was augmented with an analysis of existing procedural documentation,

FIGURE 1  Cognitive model of cardiovascular surgery. Combined RPD-Decision Ladder Cardiovascular Cognitive Model, RPD, recognition-primed decision
specifically the COCATS 4, Task Force 10 training procedure (King et al., 2015) and a stent fitting procedure (Stent: Purpose Procedure and Risks, 2017). The research team observed cardiovascular procedures at MVH, conducting pre-op and post-op interviews with the surgeon to define cognitive states and actions. Finally, procedures carried out on the low-cost cardiac catheterization simulator, were conducted by the research team to understand first-hand the complexities of the cognitive task.

A unified model representing naturalistic, analytical, and mixed decision types was synthesized by modifying and combining existing cognitive models. The RPD Model (Klein, 1993; 1999) forms the representation of expert responses to routine situations with representation of analytical decisions in nonroutine scenarios based on the Decision Ladder (Rasmussen, 1974). There are "shortcut" paths in the model representing mixed decisions, aligned with heuristics of experienced surgeons. This dynamic cognitive model represents the relative distributions of normative and descriptive modeling as determined by Craig et al. (2012).

The RPD model (Klein, 1993; 1999) is used to understand how people make quick decisions in complex situations, particularly in expert domains. The model is derived from research into intuitive decision making and assumes use of prior knowledge and pattern recognition to make decisions. There are two key elements in the RPD model: first, the way a decision maker assesses a situation and recognizes a suitable course of action, and secondly how a course of action is imagined, and potential outcomes evaluated. Both of these elements are dependent on the ability to recognize both features of the situation and corresponding actions (Klein, 1993). This model is more typical of the advanced or expert decision maker, as higher situational awareness and ability to predict outcomes based on experience enables this type of nuanced, heuristic decision making.

### TABLE 2 Case study validation scenario definition

| Scenario phase      | Description                                                                 |
|---------------------|-----------------------------------------------------------------------------|
| Procedure type:     | Planned, routine procedure—Stent fitting to correct narrowing of coronary artery. |
| Patient definition: | 58-year-old male, 6 feet tall, with a body mass index of 25                   |
| Patient preparation complications: | none                                                                               |
| Catheter selection complications: | The Fluoroscopic imaging of the patient reveals a narrower than expected vascular structure for a man this size and the initial expectations on catheter size and shape are violated. |
| Catheter insertion complications: | none                                                                               |
| Catheter maneuver complications: | The catheter maneuver is unsuccessful due to the narrowed vascular geometry. |

### TABLE 3 Case study validation scenario walkthrough with result (in bold)

| Walkthrough phase | Description                                                                                                                                                                                                 |
|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Step 1            | A 58-year-old male has been diagnosed with a narrowing of a coronary artery and has been scheduled for a stent fitting to correct the condition. The patient characteristics are within the experience of the cardiovascular surgeon and planning elements are routine.  
This follows path P1 in the cognitive model and is representative of Intuitive decision making. |
| Step 2            | The preparation is conducted by the anesthetist and the patient responds as expected.                                                                                                                        |
| Step 3            | This vascular geometry is assessed creating a decision point at D1. The vascular geometry is found to be narrower than expected in line with the scenario definition, resulting in the surgeon using their experience and associated heuristics to reselect an appropriate catheter based on this new information.  
This is a mixed Intuitive-analytical decision, following path P2. |
| Step 4            | A suitable insertion point is easily found but catheter insertion task is somewhat harder than expected. The surgeon intuitively corrects and quickly achieves a successful insertion without requiring consultation with other team members.  
This is within the bounds of the Recognition-Primed Decision model—not requiring analytical heuristics so still follows path P1. |
| Step 5            | The maneuver of the catheter to the procedure site is unsuccessful in line with the scenario definition. The surgeon corrects position and tries again but is still unsuccessful.  
Expectations are violated and path P3 is adopted. The surgeon may need to consult with external decision support and generate multiple options such as a different catheter or entry point. These options are evaluated against through a value judgement in the analytical level of the model. |
The decision ladder model (Rasmussen, 1974) is representative of both the analytical decision making paradigm and the heuristic, intuitive paradigm. In this model, the rational decision process follows the outer path of the "ladder" whereas the heuristic decision process may start and finish anywhere in the model appearing as "shortcuts" (Rasmussen, 1974). These models were combined with a single start point as in the Complex RPD Strategy Model (Klein, 1993; 1999). The three cognitive paths through the model are labelled P1 (Intuitive Decision Making), P2 (Mixed Decision Making), and P3 (Analytical Decision Making). Cognitive states are denoted by rounded boxes and actions in the square cornered boxes. The decision node represents where a surgeon's cognitive state can switch from intuitive to analytical. An additional external decision support node (labelled D2, Figure 1) was introduced in the analytical decision phase to illustrate the potential for the surgeon to increase interaction with the other members of the team to determine a course of action in a complex, unfamiliar situation. The Cognitive Model of Cardiovascular Surgery (Stone, 2020) is shown in Figure 1.

6.1 | Task 1—Argument-based validation

6.1.1 | Task 1A—Define the validation assessment question and purpose (argument based, IUA)

Our Validation Question is "Does the Cognitive Model of Cardiovascular surgery represent the underlying cognitive processes of the cardiovascular surgeon?" This case study focuses on the initial validation of a developmental cognitive model, examining the approaches, assumptions and techniques that contribute to the model as well as an asynchronous, scenario-based walkthrough assessment of the model representation and appropriateness.

6.1.2 | Task 1B—Define validation scoring interpretations framework (argument-based validity)

We defined a five-level interpretation hierarchy with inferences attributable to both the validity and reflexivity scores. The validation score interpretation framework is shown in Table 5.

6.2 | Task 2—Representation assessment (cognitive walkthrough analysis)

6.2.1 | Task 2A—Generate scenarios

Scenarios representative of the use case were developed to enable cognitive walkthrough. To ensure scenarios generated for the
Table 5: Validation score interpretation framework

| Validation status                | Interpretation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Criteria                                                                                                                                                                                                                     |
|---------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| High overall validity           | The model can be said to have a high validity for an early developmental model and is suitable for implementation in initial research studies only. Model validation should continue as part of an ongoing, iterative design process. The model has high validity scores across all validation tasks. There is good evidence that the underlying assumptions are valid, data collection techniques are sound and researcher bias has been addressed through reflexivity assessment. The model has been demonstrated to be representative. The inferences of the Interpretation framework are reasonable and the definitions of are clear, coherent, and complete. | Total VF² Score ≥ 25 (max = 30)  
Interpretation Score ≥ 7  
Representation Score ≥ 7  
Reflexivity Score ≥ 7  
Min Success Criteria Score ≥ 2  
Min objectivity Criteria Score ≥ 1 |
| Good validity                   | There is evidence that this model has good validity for an early developmental model and clear, complete, and coherent interpretations were defined. This model may be useful for implementation in initial research studies, however reflexivity scores were low so there is a remaining caveat on the potential for researcher bias. Further external confirmation of the model is required to use with confidence.                                                                                     | Total VF Score ≥ 19 (max = 30)  
Interpretation Score ≥ 6 (60%)  
Representation Score ≥ 6 (60%)  
Reflexivity Score ≥ 6 (60%)  
Objectivity score ≥ 6 (60%) |
| Poor reflexivity                 |                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                             |
| Well defined interpretation     | There is evidence that this model has good validity for an early developmental model and reflexivity assessments have been complete. This model may be useful for implementation in initial research studies, however interpretation frameworks were not provided so findings are should be treated as somewhat speculative until an interpretation framework is defined.                                                                                                     | Total VF Score ≥ 19 (max = 30)  
Interpretation Score ≥ 6 (60%)  
Representation Score ≥ 6 (60%)  
Reflexivity Score ≥ 6 (60%) |
| Poor validity                   | Underlying data and assumptions used in the development of this model were somewhat unclear, incomplete, or incoherent. Researcher bias has been assessed and interpretations are clear, however caution should be used when implementing this model outside research team development activities.                                                                                                          | Total VF Score ≥ 19 (max = 30)  
Interpretation Score ≥ 6 (60%)  
Representation Score ≥ 6 (60%)  
Reflexivity Score ≥ 6 (60%) |
| Good reflexivity                 | There are significant problems with two or more of the validation criteria. Further validation effort is required before the model can be used, even in initial research investigations.                                                                                                                                                                                                                                               | Total VF Score ≤ 19 (max = 30)  
Interpretation Score ≤ 6 (60%)  
Representation Score ≤ 6 (60%)  
Reflexivity Score ≤ 6 (60%) |
| Poorly defined interpretation   |                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                             |

*Validation Framework (VF) score defined on page 11 of the main text.

Table 6: Hybrid cognitive validation framework score summary—primary researcher

| Success criteria score | Objectivity score | Total score |
|-----------------------|-------------------|-------------|
| Task 1—Argument-based analysis | 6/6 | 0/4 | 6/10 |
| Task 2—Walkthrough analysis | 5/6 | 0/4 | 5/10 |
| Task 3—Reflexivity analysis | 6/6 | 0/4 | 6/10 |
| Total (vertical sum) | 17/18 | 0/12 | 17/30 |

*The preliminary validation framework scores from all three validation tasks and associated sub tasks are collated and summed to use in conjunction with the Interpretation Framework, Table 5.

Table 7: Hybrid cognitive validation framework score summary—including objectivity rating

| Success criteria score | Objectivity score | Total score |
|-----------------------|-------------------|-------------|
| Task 1—Argument-based analysis | 6/6 | 4/4 | 10/10 |
| Task 2—Walkthrough analysis | 4/6 | 4/4 | 8/10 |
| Task 3—Reflexivity analysis | 5/6 | 3/4 | 8/10 |
| Total (vertical sum) | 15/18 | 11/12 | 26/30 |

*The complete validation framework scores from all three validation tasks and associated sub tasks are collated and summed to use in conjunction with the Interpretation Framework, Table 5.
walkthrough were representative of different cognitive states of surgeons throughout the process, a matrix of surgical cognitive tasks corresponding to Intuitive, Mixed and Analytical Decisions was defined, see Table 4. This matrix was used to define each stage of the scenario. The scenario used in this case study is outlined in Table 2.

6.2.2 | Task 2B—Cognitive walkthrough

A cognitive walkthrough of each scenario/vignette was conducted with reference to the cognitive model. The cognitive model was scored for representativeness against the cognitive paths, actions, and decision points identified in the model in Figure 1. The output from the cognitive walkthrough is detailed in Table 3 and both initial and reflexivity scores are provided in Tables 6 and 7.

6.3 | Task 3 reflexivity assessment

6.3.1 | Task 3A—Were appropriately qualified participants used in the model development?

Underpinning assumptions for the model were developed in consultation with a cardiovascular surgeon with over 5 years’ experience of cardiac surgery. Assumptions and representations were also generated through procedural observation and consultation with procedures and tasks outlined in COCATS 4, Task Force 10 training procedure (King et al., 2015).

6.3.2 | Task 3B—Was the data collection process robust and complete during model development?

The rationale for excluding computational validation methods was explained in the development process. The breadth and depth of data sources were highlighted in the model development. The model development utilized existing research to establish a credible solution. The development steps are explicitly linked to data collection activities and establish a clear rationale for model development.

6.4 | Score summary results and interpretation guidance

The preliminary scores derived from the initial Hybrid Cognitive Validation Framework assessment of the case study model are summarized in Table 6. It can be seen from these results that there is a “0” objectivity score as the assessment was conducted by the primary researcher. In this case, the Interpretation guidance would be that this model has poor validity, despite high validation scores, as no objectivity analysis was complete at this point. The rationale for this decision is outlined in the Section “Validation Framework Implementation Scoring.” The validation procedure was repeated by a second researcher to demonstrate the improvement in scoring associated with the objectivity scoring element of the framework.

Second researcher variance in the implementation of the validation framework scoring stemmed from Tasks 3B and 4B in both Success Criteria and Objectivity components. Task 3B demonstrated the basic requirements of the framework were met, but only on a single scenario. Additionally, this was not found to be completely representative of all surgical phases. Task 4B alternatively, demonstrated that data collection covered the breadth and depth of the model for a representation to be made and collection conditions to be consistent, however, there was insufficient evidence to determine data were collected without bias or omission. The second researcher was not present for a debrief within 1 week of data collection, limiting the Objectivity score to a score of 1.

Overall, the second researcher scoring lowered the success criteria scoring from 17 to 15 but improved the objectivity scoring from 0 to 11. This underlines the importance of second researcher involvement in the assessment phase. The VF score resulting from the second researcher implementation of the case study was 26. When applied to the interpretation guide (Table 5), the cognitive model used in this case study was determined to have “High Overall Validity.”

7 | DISCUSSION AND CONCLUSION

The Hybrid Cognitive Validation Framework developed in this study was demonstrated in a case study under COVID-19 restrictions. This framework was able to establish construct validity and content validity in line with expectations given input of a second researcher to evaluate initial validation assessments. This framework provides a structured means to approach initial validation studies where traditional validation resources are either restricted or projects do not have the means to access them. Including this simple validation process in projects can help to determine early on if models have potential validity and help to develop model inputs and requirements more accurately.

The Hybrid Cognitive Validation Framework was able to provide evidence-based validity scores and associated interpretations given the COVID-19 restrictions with no requirement for face-to-face validation assessments. This study demonstrated that the framework can be easily implemented by a small team with limited resources, highlighting the importance of objectivity elements in the method. The argument-based validation elements used are comparable with those outlined by Kane (2013). The reflexivity assessments are comparable with the process outlined by Davies and Dodd (2002), however these are contingent on review by a second researcher or external SME.
A key limitation of this framework is the reliance on retrospective, scenario-based walkthroughs to replace concurrent assessment during procedures. The impact of this limitation is hard to quantify but while it may be considered to have lower credibility compared to existing methods, it fulfills the goal of model validation requiring no direct contact and minimal reliance on remote usability and observational studies. In this study, we discuss the validation of cognitive models under COVID-19 restrictions. These restrictions will also impact cognitive model development; however, this was not addressed in this study as our model was developed before the restrictions.

This initial case study implementation of the Hybrid Cognitive Validation Framework has shown promise to enable early validation with limited resources, the development process was rapid, and many lessons were learned along the way. Adapting to new ways of working has been necessitated by the COVID-19 restrictions that have become the new normal. The framework detailed in this study should be considered the starting point to refine and adjust as new evidence and experience informs its development, particularly regarding tuning of the validation scoring elements and their links to the defined implications.

The Hybrid Cognitive Validation Framework allows researchers to rapidly establish initial validity for cognitive models, especially given the restrictions associated with COVID-19, and other situations where face-to-face contact with SMEs may be limited, due to location or availability of the experts. This implementation focuses on the initial validation of the cognitive model of cardiovascular surgery, but we believe this approach could be easily used to validate any cognitive model, particularly those relating to decision making in complex environments, where access to expert input is limited, such as military, petrochemical, medical, or aviation. The keys to broader implementation of this method are the ability to establish the IUA and validity arguments defined in the argument-based validation method along with the development of credible scenarios with tasks that represent the potential cognitive states and paths defined in the cognitive model (Kane, 2006; 2013).

While we believe this validation framework has utility under the circumstances identified, it is more prescriptive than other methods discussed in this paper and does not cover criterion validity. Ideally, we would like to establish concurrent validity through correlation tests between the predicted model state and concurrent assessments of a surgeon's employed mental model assessed by SMEs. This approach would be potentially less subjective and easier to compare using quantitative tests. While this establishes further validity evidence, it is potentially much more complex and requires access to resources that are not compatible with the rationale of an early-stage, low-cost validation approach presented here. The use of interview data as a reference for model validity (Thoroman et al., 2019) would provide a potentially more robust means to gather validity data. A simulation approach, as employed by Vinod et al. (2016) could potentially establish more objective validity data but has potential corresponding validity issues arising from the simulation of human agents in a specialized role. Stanton (2016) notes that small assessment groups are frequently a problem with validation in Human Factors Engineering, and this case study was no exception, limiting the confidence in the conclusions until further research can be completed.

Due to time constraints, this study only considers a single scenario for the walkthrough analysis validation with a single SME. The next stage in the development of this validation framework will be to develop a more extensive set of scenarios for the cognitive walkthrough to establish more evidence for model validity. To enable this, it is expected that a more detailed scoring framework will be required to bridge the gap between the reviewer's cognitive walkthrough responses and the validity scores assigned in the validation interpretation framework.

COVID-19-like restrictions also have the potential to disrupt the development of cognitive models, before, or in parallel with validation activities. Future studies should address potential methods to address the impact on model development.

The detail in the instructions given is another potential limitation of this study, further development of the instructions and the presentation of the cognitive walkthrough task is important to ensure clarity and consistency of interpretation between reviewers.

Reliability and Validity are closely related and often combined to establish confidence in a model. We have not considered reliability in this study, but in the future, this could be established with intra-rater agreement analysis using Pearson's correlation test.

As part of an iterative validation process, we recommend conducting a full validation in line with the procedure defined by Craig et al. (2012) and compare to the validation results achieved in this study. The Hybrid Cognitive Validation Framework was primarily implemented by a researcher aware of the development process and somewhat familiar with the model. We plan to conduct usability assessment and refine the design of the validation framework based on the results. To confirm the utility of the framework, it should be implemented by external research teams looking for a lightweight, initial validation approach for cognitive modelling.

The value of this Hybrid Cognitive Validation Framework comes in the early stages of model development to ensure validation is considered at an early stage and appropriate evidence captured. This framework can be easily and quickly implemented by a small research team and provides a structured validation method to increase confidence in a cognitive model and provide evidence to support validity claims in the early stages of development. This method has been derived from the necessity of the COVID-19 response requiring no direct contact, however we believe that it can have broader application to lower costs and reduce timelines, enabling faster progress in the development of cognitive engineering systems.
DATA AVAILABILITY STATEMENT
Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

ORCID
Paul B. Stone http://orcid.org/0000-0002-9741-1919
Mary E. Fendley http://orcid.org/0000-0001-5493-1845
Subhashini Ganapathy https://orcid.org/0000-0001-5228-4816

REFERENCES
American Psychological Association. (American Educational Research Association, & National Council on Measurement in Education 1954). Technical recommendations for psychological tests and diagnostic techniques (51). American Psychological Association. No. 2.
Annett, J. (2002). A note on the validity and reliability of ergonomics methods.
Ashraf, B.N. (2020). Economic impact of government interventions during the COVID-19 pandemic: International evidence from financial markets. Journal of behavioral and Experimental Finance, 27, 100371.
Belkin, N.J. (1984). Cognitive models and information transfer. Social Information Studies, 4(2-3), 111–129.
Cooper, R., Fox, J., Farringdon, J., & Shallice, T. (1996). A systematic methodology for cognitive modelling. Artificial Intelligence, 85(1-2), 3–44.
Cornellissen, M., McClure, R., Salmon, P.M., & Stanton, N.A. (2014). Validating the strategies analysis diagram: Assessing the reliability and validity of a formative method. Applied Ergonomics, 45(6), 1484–1494.
Craig, C., Klein, M., Griswold, J., Gaitonde, K., McGill, T., & Halldorsson, A. (2012). Using cognitive task analysis to identify critical decisions in laparoscopic environments. Human Factors, 54(6), 1025–1039.
Cronbach, L.J., & Meehl, P.E. (1955). Construct validity in psychological tests. Psychological Bulletin, 52(4), 281–302.
David, N. (2013). Validating simulations. In Simulating social complexity (pp. 135–171). Springer.
Davies, D., & Dodd, J. (2002). Qualitative research and the question of rigor. Qualitative Health Research, 12(1), 279–289.
DeWine, M., Husted, J., & Acton, A. (2020). Director’s Stay Safe Ohio Order. Ohio Department of Health. https://coronavirus.ohio.gov/static/publicorders/Directors-Stay-Safe-Ohio-Order.pdf
Embretson, S.E. (1983). Construct validity: Construct representation versus nomothetic span. Psychological Bulletin, 93, 179–197.
Hale, T., Petherick, A., Phillips, T., & Webster, S. (2020). Variation in government responses to COVID-19. Blavatnik school of government working paper, 31.
Haleem, A., Javid, M., Vaishya, R., & Deshmukh, S.G. (2020). Areas of academic research with the impact of COVID-19. The American Journal of Emergency Medicine, 38, 1524–1526.
Hayes-Roth, B., & Hayes-Roth, F. (1979). A cognitive model of planning. Cognitive Science, 3(4), 275–310.
Kane, M. (2006). Validation. In (Ed.) Brennan, R., Educational measurement (4th ed., pp. 17–64). American Council on Education and Praeger.
Kane, M. (2013). The argument-based approach to validation. School Psychology Review, 42(4), 448–457.
Keehner, M., Gorin, J.S., Feng, G., & Katz, I.R. (2017). Developing and validating cognitive models in assessment: The Handbook of Cognition and Assessment: Frameworks, Methodologies, and Applications, 75–101.
King, S.B., Babb, J.D., Bates, E.R., Crawford, M.H., Dangas, G.D., Voeltz, M.D., & White, C.J. (2015). COCATS 4 Task Force 10: Training in cardiac catheterization. Journal of the American College of Cardiology, 65(17), 1844–1853.
Klein, G.A. (1993). A recognition-primed decision (RPD) model of rapid decision making. Decision Making in Action: Models and Methods, 5(4), 138–147.
Klein, G.A. (1999). Sources of power: How people make decisions. MIT press.
Landry, M., Malouin, J.L., & Oral, M. (1983). Model validation in operations research. European Journal of Operational Research, 14(3), 207–220.
Law, A.W.D.K. (1991). Simulation Modeling and Analysis.
Lewis, C., Polson, P.G., Wharton, C., & Riemann, J. (1990). March Testing a walkthrough methodology for theory-based design of walk-up-and-use interfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 235–242.
Lintern, G. (2010). A comparison of the decision ladder and the recognition-primed decision model. Journal of Cognitive Engineering and Decision Making, 4(4), 304–327.
Middleton, F. (2019). The 4 Types of Validity. Website, ReScribbr.com (retrieved 12/12/2020) https://www.scribbr.com/methodology/types-of-validity/
Miliello, L.G., & Hutton, R.J. (1998). Applied cognitive task analysis (ACTA): A practitioner’s toolkit for understanding cognitive task demands. Ergonomics, 41(11), 1618–1641.
Rasmussen, J. (1974). The human data processor as a system component. Bits and pieces of a model. Report No. RISE –M-1722.
Rupp, A.A., & Leighton, J.P. (Eds.). (2016). The Wiley handbook of cognition and assessment: Frameworks, methodologies, and applications. John Wiley & Sons.
Silva, C., Vieira, J., Campos, J.C., Couto, R., & Ribeiro, A.N. (2020). Development and validation of a descriptive cognitive model for predicting usability issues in a low-code development platform. Human Factors, 0018720820920429. https://doi.org/10.1177/0018720820920429
Soh, B.K. (2007). Validation of the recognition-primed decision model and the roles of common-sense strategies in an adversarial environment (Doctoral dissertation, Virginia Tech).
Stanton, N.A. (2016). On the reliability and validity of, and training in, ergonomics methods: A challenge revisited. Theoretical Issues in Ergonomics Science, 17(4), 345–353.
Stanton, N.A., & Baber, C. (2005). Validating task analysis for error identification: Reliability and validity of a human error prediction technique. Ergonomics, 48(9), 1097–1113.
Stanton, N.A., & Stevenage, S.V. (1998). Learning to predict human error: Issues of acceptability, reliability, and validity. Ergonomics, 41(11), 1737–1756.
Stanton, N.A., & Young, M.S. (1999). What price ergonomics? Nature, 399(6733), 197–198.
Stent: Purpose, Procedure, and Risks. (2017). Retrieved 19 April 2020, from https://www.healthline.com/health/stent#procedure
Stone, P.B. (2020). Improving Decision Support Systems Through Context and Demand Aware Augmented Intelligence in Dynamic Joint Cognitive Systems. Unpublished manuscript.
Strube, G. (2001). Cognitive modeling: research logic in cognitive science, 2124–2128.
Sy, M., O’Leary, N., Nagraj, S., El-Awaisi, A., O’Carroll, V., & Xyrichis, A. (2020). Doing interprofessional research in the COVID-19 era: A discussion paper. Journal of Interprofessional Care, 34(5), 600–606.
Thoroman, B., Salomon, P., & Goode, N. (2019). Evaluation of construct and criterion-referenced validation of a systems-thinking based near miss reporting form. Ergonomics, 63(2), 210–224.
Vinod, A.P., Tang, Y., Oishi, M.M., Sycara, K., Lebiere, C., & Lewis, M. (2016). Validation of cognitive models for collaborative hybrid systems with
discrete human input. In 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 3339-3346). IEEE.

Wagenaar, W.A., Hudson, P.T., & Reason, J.T. (1990). Cognitive failures and accidents. *Applied Cognitive Psychology, 4*(4), 273–294.

Woods, D.D. (1985). Cognitive technologies: The design of joint human-machine cognitive systems. *AI magazine, 6*(4), 86.

World Health Organization. (2020). COVID-19 Weekly Epidemiological Update. Retrieved November 11 from https://www.who.int/publications/m/item/weekly-epidemiological-update—10-november-2020.

**How to cite this article:** Stone, P.B., Nelson, H.M., Fendley, M.E., & Ganapathy, S. (2021). Development of a novel hybrid cognitive model validation framework for implementation under COVID-19 restrictions. *Hum. Factors Man, 31*, 360–374. https://doi.org/10.1002/hfm.20904