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Volume 2

Effects of Environmental Conditions on Manual Actions for Flood Protection and Mitigation

Review of the Research Literature

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Effects of Environmental Conditions on Manual Actions for Flood Protection and Mitigation

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) is carrying out a Probabilistic Flood Hazard Assessment Research Program to enhance NRC's risk-informed and performance-based regulatory approach to external flood hazard assessment. One of NRC's initiatives is to better understand the actions that nuclear power plant (NPP) licensees have planned to take outside of the main control room to prepare for, protect against, and mitigate the effects of external flooding events. The Pacific Northwest National Laboratory (PNNL) conducted a comprehensive review of research literature describing how the environmental conditions (ECs) associated with flooding events might affect performance of flood protection and mitigation actions. To support and inform the literature review, this report identifies and characterizes the ECs associated with flooding events; these conditions include heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning. Based on a review of NRC staff assessments, flooding walkdown reports at 60 NPP sites, individual NPPs' procedures (e.g., Abnormal Operating Procedures) that were available, and available descriptions of some activities related to diverse and flexible coping strategies, or FLEX, the report identifies and characterizes a set of manual actions (MAs). These example MAs would be performed at and around NPP sites (outside the main control room) in preparation for or in response to a flooding event.

This report provides an approach for decomposing the MAs into simpler units—tasks, subtasks, specific actions and performance demands—to facilitate assessment of EC impacts consistent with approaches in human performance research literature. The review of the research literature summarizes the state of knowledge concerning the effects of the ECs in terms of their mechanisms of action, effects on performance, and potential mitigation measures. Based on this review, the report presents a typology of performance demands that includes detecting and noticing, understanding, decision-making, action, and teamwork that provides a basis for applying research findings to estimate performance impacts. The report presents a conceptual framework that illustrates the relationships among ECs, MAs, and performance. The impact assessment approach is illustrated using a proof-of-concept method for an example MA. Based on the findings of the research literature review and the conceptual framework demonstrated for impact assessment, opportunities for future research are described.

This work is presented in two volumes. Volume 1 describes the flood mitigation actions, a typology of performance demands, a conceptual framework with a proof of concept example and a summary of the review of literature of the impacts of environmental conditions on human performance. Volume 2 provides the complete literature review of environmental conditions on human performance, with a separate detailed chapter for each of the identified environmental conditions identified as impacting flood mitigation and performance actions.

FOREWORD

The key research question addressed in this report is what and how can existing human performance literature be used to inform the impact of environmental conditions on flood protection and mitigation procedures conducted in preparation for or during flooding events at nuclear power plants? This report was developed to provide insight into the actions that nuclear power plant licensees have planned to take to prepare for and mitigate the effects of external flooding events. This goal was undertaken as a part of the Probabilistic Flood Hazard Assessment Research program to enhance the NRC's risk-informed and performance-based approach to external flood hazard assessment.

Lessons learned from flood walkdowns conducted in response to the Near-Term Task Force Recommendations following the earthquake at the Fukushima Dai-ichi facility demonstrated that environmental conditions can influence human performance and human error probabilities, especially for outdoor manual actions during flooding, and may degrade or completely preclude an individual's capability to perform the necessary actions. The degradation in performance can be measured by the (usually) additional time it may take to complete an action or by the (usually) increased probabilities of making an error. In this report, the primary focus is on the first measure (i.e., increase in task performance time); however, the conceptual framework could also be extended to support the estimation of increases in error rates and error probabilities.

This report presents a conceptual approach to assessment of manual actions performed in response to external flooding and the human performance literature findings to connect the diverse information base. The report does not present a complete method for site-specific performance impact assessment and stops well short of developing a Human Reliability Analysis (HRA) method. However, the human performance literature review results may be useful in developing such a method.

The objectives of this work were to:

1. identify and characterize typical flood protection and migration actions, referred to as manual actions,
2. review, update and synthesize the important environmental conditions that affect human performance of the flood manual actions,
3. develop a framework in which to assess the impact of the environmental conditions which fits the needs for flood manual actions and the environmental conditions likely to be present,
4. summarize the existing human performance literature within the example framework, and
5. provide a simple proof-of-concept example of the approach.

Volume 1 of this report includes objectives 1-5, while Volume 2 thoroughly documents the review of existing human performance literature that relates to environmental conditions.

The key findings from this research are:

- A set of manual actions associated with flood protection and mitigation procedures were identified from a variety of sources including plant walk downs, procedures and FLEX strategies.
- Environmental conditions associated with flooding events were identified:
    - heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning
- An approach for decomposing the flood manual actions into simpler units—tasks, subtasks, specific actions and performance demands—to facilitate assessment of environmental conditions impacts consistent with approaches in human performance research literature was developed as a basis for applying research findings to estimate performance impacts.
    - Performance demands: detecting and noticing, understanding, decision-making, action, and teamwork
- A review of research literature provided the information to summarize the state of knowledge concerning the effects of the environmental conditions in terms of their mechanisms of action, effects on performance, and potential mitigation measures.
- Based on this review, a conceptual framework that illustrates the relationships among environmental conditions, flood manual actions, and performance demands was presented
    - The impact assessment approach was illustrated using a proof-of-concept method for an example flood manual action
    - A full assessment would require site specific information and likely a method of expert elicitation to apply impact factors to specific actions
- The extension of this impact assessment approach to generalized actions that could be assessed for common flood manual actions and then applied for different site-specific conditions was discussed.
    - An example assessment using IMPRINT (a task analysis software) was conducted which allowed assessment of impacts of multiple environmental conditions, impacts on estimated time, error rates, and uncertainty.
    - Opportunities for future research to fill information gaps, reduce the limitations of the conceptual framework and other steps to a full analysis were discussed.

This report identifies flood protection and mitigation actions at nuclear power plants, environmental conditions that affect the performance of those actions, and set of performance demands that can be used within the presented conceptual framework as a basis for applying research literature findings to estimate performance impacts. The utility of the conceptual framework and review information is demonstrated in a simple proof of concept example and a more complex site-specific task analysis training demonstration. These results can be used to inform development of an HRA method or provide insights on the impacts of human performance on flood protection and mitigation procedures.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) is conducting a Probabilistic Flood Hazard Assessment (PFHA) Research Program that is a set of research projects and tasks that the Office of Nuclear Regulatory Research (RES) is implementing to enhance NRC's risk-informed and performance-based regulatory approach to external flood hazard assessment. The PFHA plan is designed to support development of regulatory tools (e.g., regulatory guidance, standard review plans) for permitting new nuclear sites, licensing activities for operating and new nuclear facilities, and oversight activities (e.g., inspections, Significance Determination Process (SDP) of operating facilities. As a part of the PFHA plan and Fukushima Near-Term Task Force (NTTF) activities, the NRC undertook several initiatives to ensure that actions taken outside the main control room required for flood protection and mitigation are both feasible and reliable. One of those initiatives was to better understand the actions that nuclear power plant (NPP) licensees have planned to take outside the main control room to prepare for, protect against, and mitigate the effects of such external flooding events, including lessons learned from implementation of NTTF recommendations.

The purpose of this report is to review human performance research literature and compile information pertinent to assessing the impacts of environmental conditions (ECs, e.g. heat or wind) accompanying external floods on the performance of human actions. These actions, specified in flood protection and mitigation procedures, are referred to in this report as manual actions (MAs). A primary objective is to provide a conceptual framework that makes this information useful. This project updates and expands the previous review of the research literature in NUREG/CR-5680 (Echeverria et al., 1994). The scope of this project stops short of characterizing the MAs or ECs at a particular plant or developing and testing a method for applying the research results to estimate the impacts on the performance of specific MAs. Therefore, the project scope does not extend to (1) consideration of the site-specific context that determines the parameters of the MAs and (2) addressing how variations in individual attributes (e.g., knowledge, training, preparedness, organizational role, and fitness) might affect performance. Based on the scope, the assumptions were that (1) the flood protection and mitigation procedures are established, appropriate, and feasible; (2) the individuals performing the MAs are trained and have necessary equipment and access; (3) the staffing levels and crew composition are adequate; and (4) the individuals performing the MAs would be fit for duty and not fatigued. Consideration of other factors known to influence performance were excluded; for example, individual characteristics (e.g., gender, age, emotions, innate ability, and physical condition), the availability of materials and equipment, the quality of plant procedures, or training. These assumptions and exclusions focused the work on describing the effects of ECs on performance of MAs with reference to a baseline metric (i.e., performance time, error rate, or probability of failure for completing an MA by a fit, knowledgeable, and adequately staffed crew under ECs that do not impact performance). The impact of ECs is expressed as an increase in performance time, error rate, or probability of failure for completing an MA.

To inform and support the conceptual framework, the flood hazard was characterized across U.S. NPP sites. Eleven environmental conditions[1] that may accompany various flood causing

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[1] The eleven identified environmental conditions are heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning.

mechanisms were identified, considering the geographical diversity of the locations of NPPs in the U.S. MAs were characterized using (1) an analysis of the NRC staff assessments of NPP flooding walkdown reports, (2) a review of five available individual plant procedures, and (3) a description of diverse and flexible coping strategies, or FLEX procedures. The research team decomposed the MAs into their simpler elements (e.g., tasks, subtasks, and specific actions) using a task analysis approach.

To characterize human physiological and cognitive capabilities that are required for successful completion of specific actions, and in turn, higher-level subtasks, tasks, and MAs, human performance taxonomies were reviewed. Combining three such human performance taxonomies - the performance abilities identified in NUREG/CR-5680 Volume 2, the taxons used by O'Brien et al. (1992), and the macrocognitive functions identified in NUREG-2114 (USNRC, 2016b) - the research team developed a taxonomy of nine performance demands[2].

Environmental conditions can adversely affect human performance. These potential effects (11 ECs affecting the 9 established performance demands) are the key components of impact assessment in the conceptual framework, and result in the increase of performance time, error rate, or probability of failure for completing an MA. For example, gross motor actions such as walking can be significantly affected by impeding forces from standing and moving water, fine motor actions can be significantly affected by cold, and sustained heat exposure can affect memory and vigilance.

To establish the impact assessment approach, the research team reviewed (1) existing impact assessment methods for NPPs, (2) assessment methods use in other domains where tasks are typically less highly proceduralized and more physically demanding, and (3) existing task and human ability typologies. Based on this review, the research team concluded that adapting a task analysis framework developed by the U.S. Army Research Laboratory offered an advantageous method to relate research findings to performance impacts. The major difference between this approach and that used in some NPP human reliability analyses (HRAs) is a greater emphasis on physical actions. This was selected because flood protection and mitigation activities often involve considerable movement and exertion and an expansion of roles to include plant staff who are not licensed or field operators.

The research literature indicated that ECs' impact on human performance could be characterized though their effects on performance demands. The specific actions discussed in this report are derived from task analysis, emphasizing the performance demands they impose. For example, a specific action, "unsheltered walking 400 m from sheltered point A over flat ground to sheltered point B on Site S," involves walking, which is a gross motor action, although some detecting and noticing as well as decision-making are required. The framework links the research findings on human performance to the assessment of EC impacts on specific actions via their corresponding performance demand compositions (i.e., in the above example, the impact of prevailing ECs on walking would be estimated via the ECs' effects on gross motor action, detecting and noticing, and decision-making). The specific actions derived from MAs at a particular NPP site would contain site-specific information (i.e., the site-specific facility layout, topography, and task sequence and context). It may also be possible, for some needs, to group multiple, similar specific actions into categories, termed generalized actions that are

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[2] The nine performance demands are: (1) detecting and noticing, (2) understanding, (3) decision-making, (4) action – fine motor, (5) action – gross motor, (6) action – other neurophysiological functions, (7) teamwork – reading and writing, (8) teamwork – oral communication, and (9) teamwork – crew interaction.

independent of site and task contexts. This approach would provide a way to transfer knowledge and experience gained from relatively few site-specific task analyses across NPP sites. The research team noted that performance demand profiles[3] can be used to consistently define generalized actions with wide applicability across NPP sites.

These steps to characterize flood protection and mitigation procedures, identify environmental conditions, develop a performance demand typology and an approach to assess the impact of the environmental conditions on the human performance of these action. EC effects on performance demands that have been documented in the literature were summarized and categorized into four different levels of knowledge, based on the extent and quality of the research available. The levels range from identified quantitative impact (Level 1), to quantitative thresholds (Level 2), to qualitative information (Level 3) and to an information gap (Level 4). This first volume of this report summarizes the key results from the literature review, while the second volume provides full details of the literature related to the impacts of ECs on human performance. The research team concluded there are significant research gaps in the human performance literature. Moreover, relatively modest progress has been made in quantifying the effects of ECs across the range of performance demands pertinent to manual actions since preparation of NUREG/CR-5680 (Echeverria et al., 1994). The literature search did not identify any large-scale ongoing or upcoming research programs from which major advances might be expected. Consequently, it appears likely that progress will be largely incremental in the upcoming years. Therefore, application of an impact assessment approach would need to innovatively and consistently apply the currently available knowledge. Nonetheless, these research gaps could be addressed by conducting sensitivity analyses to determine EC-performance demand combinations that most affect flood protection and mitigation MAs. Insights gained from sensitivity analyses could help reduce uncertainties about the estimation of impacts and direct future research.

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[3] The performance demand profile of a specific or a generalized action is defined by the relative contributions of the different performance demands required to perform the action.

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ABBREVIATIONS AND ACRONYMS

°C	degree(s) Celsius
°F	degree(s) Fahrenheit
ACGIH	American Conference of Governmental Industrial Hygienists
ARL	U.S. Army Research Laboratory
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BEI	Biological Exposure Indices
cd	candela
Clo	clothing thermal insulation index
cm	centimeter(s)
cm/s	centimeter(s) per second
CRI	color rendering index
dB	decibel(s)
dB(A)	A-weighted decibel
EC	environmental condition
EPA	U.S. Environmental Protection Agency
FCM	flood causing mechanism
FHWA	Federal Highway Administration
FLEX	diverse and flexible coping strategies
ft	foot(feet)
ft/s	foot(feet) per second
ft^2/s	square foot(feet) per second
FNU	Formazin Nephelometric Unit
GA	generalized action
g	gram(s) or acceleration due to gravity
g/L	gram(s) per liter
h	hour(s)
HEP	human error probability
HFE	human failure event
HRA	human reliability analysis
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society
IMPRINT	Improved Performance Research Integration Tool
in.	inch(es)
IOSH	Institute of Occupational Safety and Health
ISO	International Standards Organization

kCal	kilocalorie
kg/m^3	kilogram(s) per cubic meter
km	kilometer(s)
km/h	kilometer(s) per hour
km/s	kilometer(s) per second
kt	knot(s)
lb/ft^3	pound(s) per cubic foot
LED	light-emitting diodes
LIP	local intense precipitation
m	meter(s)
m^2/s	square meter(s) per second
MA	manual action
mi^2	square mile(s)
MCR	main control room
min	minute(s)
mm	millimeter(s)
mm/hr	millimeter(s) per hour
m/s	meter(s) per second
mph	mile(s) per hour
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
nm	nanometer(s)
N/m^2	newton(s) per square meter
NOAA	National Oceanic and Atmospheric Administration
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NTTF	Near-Term Task Force
NTU	Nephelometric Turbidity Unit
NWS	National Weather Service
OSHA	Occupational Safety and Health Administration
PIF	performance influencing factor
PRA	probabilistic risk assessment
PSF	performance shaping factor
R2	coefficient of determination
RG	Regulatory Guide
rms	root-mean-square
rms-g	root-mean-square acceleration
s	second(s)
SA	specific action
SAVE-IT	Safety Vehicle Using Adaptive Interface Technology

SDP	Significance Determination Process
SI	International System (of units)
SPAR-H	Standardized Plant Analysis Risk-Human Reliability Analysis
SWV	safe walking velocity
THERP	Technique for Human Error-Rate Prediction
TLV	threshold limit value
USGS	U.S. Geological Survey
UV	ultraviolet
VO_2	maximum volume of oxygen
WBGT	wetbulb globe temperature

1 INTRODUCTION

Volume II is a companion to Volume I, which provides the impact assessment framework that the information in this volume supports. An extensive review of the research literature about how environmental conditions affect human performance was conducted. The results of that review are presented in this volume.

1.1 Purpose and Method

The goal of the literature search and review was to build a reasonably complete, multidisciplinary knowledge bank from which to evaluate and summarize research findings addressing the effects of environmental conditions (ECs) associated with potential flooding events at U.S. nuclear power plants (NPPs) on salient dimensions of human performance, termed performance demands in this document. Assembling the research literature allowed for addressing the consistency of findings regarding the impacts of ECs on performance and identifying gaps in the research that suggest areas requiring further study.

As discussed in Volume I, preparation for the literature review included identifying and characterizing the range of ECs and type of activities pertinent to the preparation and response to flooding conditions at U.S. NPPs. The following environmental conditions are associated with flooding event ECs: heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning. Pertinent flood protection and mitigation activities, termed manual actions (MAs) were identified and characterized by reviewing several sources as described in Chapters 3 and 6 in Volume I.

The literature review was performed to update and extend the review reported by Echeverria et al. (1994); hence, this review built on the research literature identified in the 1994 review. Overall, the present search was designed to find research that addressed the identified ECs, the mechanisms by which these ECs could affect MAs, and the underlying nature of conditions that affect performance by imposing demands on human abilities. Initially, the search used a list of performance and activity search terms that included both (1) entire tasks and types of MAs (e.g., walking, vehicle operation, construction) and (2) component performance demands. Preliminary review of the results, augmented with pertinent U.S. Nuclear Regulatory Commission Human Reliability Analysis methodologies, led to refinement of the performance demands to those listed in Table 1.1. Alternative terms for these performance demands were also pursued as they were discovered in the literature (e.g., names of specific vigilance tasks.[1] often used in the literature).

As the scope of the literature review was being clarified, the set of databases to be searched were identified and extended. The intent was to capture a set of databases that would represent the discipline areas most relevant to the research problem. These ultimately covered cognitive and experimental psychology, human factors, industrial engineering, industrial hygiene, environmental and occupational health, environmental physiology, and medicine. The chosen databases included Google Scholar, PsychInfo, Web of Science, Science Direct, PubMed,

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[1] Throughout this volume, the term “tasks” most typically reflects its use in the research literature (i.e., an assignment given to or performed by the subjects being studied). The exception is where it is specifically noted as referring to tasks as an element of decomposition of MAs into tasks and/or subtasks as described for the System for Performance Impacts from Conditions in the Environment framework in Chapter 3. In the research literature, the term task is generic in that it can refer to any level of decomposition or composition.

Table 1.1 Primary performance demands search terms

Performance Demand	Search Term
Detecting and noticing	Attention, memory, vigilance, switching, acuity, perception, threshold perception; sensation, visual recognition
Understanding and diagnosis	Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, integrating
Decisionmaking	Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating options, selecting options
Action	Fine motor skills – discrete, continuous; manual dexterity; gross motor skills – heavy, light; neurophysiology
Teamwork	Reading and writing; oral communication, electronic communication; cooperation, crew interaction, command and control

Defense Technical Information Center, and Medline. Professional and government agency websites and technical reports were also searched for relevant content. These included the NRC, National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), U.S. Environmental Protection Agency (EPA), National Weather Service (NWS); National Oceanic and Atmospheric Administration (NOAA), American Conference of Governmental Industrial Hygienists (ACGIH), and Illuminating Engineering Society (IES). For each EC identified, within each of these information sources, searches for each of the performance demand terms identified in Table 1.1 were conducted.

A wide variety of information products were targeted for selection within these sources, including scholarly articles, books, conference proceedings, dissertations, professional and regulatory organization regulations, guidelines, and fact sheets. Meta-analyses and reviews of the research literature were given special attention. The research team supplemented the formal literature search with direct inquiries (by phone or email) to researchers and practitioners currently engaged in the areas of interest. These contacts were asked to identify classical and newly emergent resources that had been found useful in ongoing work and others working in the field who might provide similar recommendations. For the five ECs addressed by Echeverria et al. (1994), special attention was given to research published after their review, because one goal of the project was to determine subsequent advancements in the knowledge about these ECs.

As documents were found, the searchers scanned the title and abstract of each item, liberally reserving those documents that appeared relevant to human performance effects of the given EC, while discarding those that clearly were not. This produced an initial set of candidate documents. Members of the research team also introduced candidate documents drawing from their past experience with EC performance effect combinations. Of note, the research team members represented the fields of cognitive and experimental psychology, human factors, industrial hygiene, environmental and occupational health and safety, and environmental science. Further, the original Echeverria et al. (1994) review provided both a baseline of knowledge and a base against which to identify major advancements during the interim period.

Once the relevant documents identified in the search were located, each of them was reviewed, identifying notable EC effects found on the various performance demands. Simultaneously, they identified additional references from citations in the documents that appeared relevant. Citations to identified articles also were examined, particularly those pointing to reviews of subsequent integrated reviews and/or meta-analyses (i.e., a forward search process conducted until reaching contemporary research). This process generated a second iteration of the literature search. These articles were read by the subject matter experts, who once again noted any references that had not been identified during earlier phases. The process was repeated until the lack of new, relevant documents indicated that the relevant research literature had been effectively identified and reviewed.

1.2 Overview of Existing Literature

The environmental effects research literature represents a long and diverse history of research into human behavior and performance. Researchers from a wide range of disciplines, with differing purposes, theoretical frameworks, and methodological approaches have contributed to the research literature. This long history and study diversity provide opportunities for reexamination, validation, and evolution as well as adding valuable breadth of focus. It also creates a number of challenges for those attempting to aggregate, integrate, and summarize the findings from this research (see NUREG/CR-5680, Echeverria et al., 1994; Gaoua, 2010; Taylor et al., 2016). Key among these are:

- inconsistencies and variability in terminology and categorization of effects
- insufficient specification of and variability in population characteristics, treatments/conditions, and controls small study populations not representative of the workforce
- gaps in examination of the full range of the salient ECs
- shortfalls in examination of the full range of potential effects at equivalent levels of disaggregation
- broad gaps in examination of co-occurring ECs.

Categorization of performance effects, especially cognitive and affective effects, also remains somewhat problematic. In part, this is due to the variability with which researchers have variously labeled and aggregated results in their studies (i.e., tasks, tests, test panels, and data). Also, in part, this has been due to a fundamental difficulty in accurately characterizing the performance demands of a task (i.e., the observed behavior or experimental test). Different tasks create performance demands that activate different patterns of brain regions (e.g. Qian et al., 2013). Further adding to the categorization challenge is that experience with a task can profoundly alter brain patterns, and hence the appropriate task classification (Bittner, Jr. et al., 1986).

The focus and extent of research have been influenced by the availability of resources and the disciplinary interests and capabilities of those conducting the research. These, in turn, have been influenced by: (1) the ever-changing problems/issues of those with the resources to fund research, (2) the prevailing theoretical and methodological issues and available research tools, and (3) evolving ethical and safety considerations. Not surprisingly, the greatest research attention has been given to the ECs that have the greatest potential to affect workers in industrial settings (i.e., heat, noise, vibration, lighting), military personnel (e.g., heat, cold, noise), and operators of vehicles (e.g., lighting, precipitation), and on those illuminating how the physiological/cognitive/affective systems of theoretical interest respond (e.g., heat, cold, lighting, noise, vibration). Some research has also been focused on developing equations/models that characterize the mechanical effects of physical forces (e.g., pressure, drag, and friction) on performance (e.g., wind, standing and moving water, ice and snowpack).

Echeverria et al. (1994, pp. 8–5) noted two major trends in the findings from research concerning effects induced by ECs. These included discomforts caused by excess exposure and disruption or interference with motor performance (rather than with mental performance). However, they added the caveat that the description of motor versus mental performance might be due to an artifact of experimental methods. They also noted that there was considerable evidence that complex tasks (especially dual tasks) are more sensitive to environmental stressors than simple, single tasks. Taylor et al. (2016) made the same observation, while acknowledging the continuing challenge of categorizing simple and complex tasks, particularly where extended complex task experience and practice may have rendered a task effectively simple. Echeverria et al. (1994) further recommended that future research incorporate improved cognitive models to better characterize the cognitive effects of exposure to environmental stressors. The research conducted since the early 1990s has seen the introduction of improved cognitive models and investigative tools, as discussed below (Parasuraman & Wilson, 2008; Petersen & Posner, 2012; Qian et al., 2013).

1.3 Knowledge Advances

Over the two decades since the previous review (NUREG/CR-5680, Echeverria et al., 1994) the various disciplines have developed increasingly sophisticated theories, techniques, and tools.

1.3.1 Neuropsychological Research Tools and Methods

In addition to advances in test battery development motivated by Echeverria et al. (e.g. Echeverria et al., 2002; McCallum et al., 2005) developments have included refinements in biochemical assays, brain imaging, and continuous monitoring equipment. This has enabled a better understanding of the chemical and neurological functioning of the brain and its interaction with the body (Lupien et al., 2007; Parasuraman & Wilson, 2008; Paulus et al., 2009; Petersen & Posner, 2012; Proctor & Vu, 2010). This research has also made considerable progress in clarifying the mechanisms that link the ECs with their cognitive, behavioral, and affective effects and effects on physical performance. As discussed below, considerable progress has been made in clarifying the mechanisms by which discomfort, anxiety, and perceptions of fear—common features of exposure to the ECs that might accompany flooding conditions—affect performance. It has also highlighted the central role attentional demands play in the pattern of performance effects that result.

1.3.2 Growing Recognition of the Central Role of Effects on Attentional Demand

The greatest knowledge increase since the 1994 review may be a greater appreciation and understanding of the broad role that attentional demand plays in the effects of exposure to a range of ECs (e.g. Lupien et al., 2007; Petersen & Posner, 2012; Taylor et al., 2016; Wickens et al., 2016) Echeverria et al. (1994) noted the classical inverted-U hypothesis and the research interest in the performance effects of the attentional demands (e.g., operator workload and many other attentional demand terms) created by changing, distracting, uncomfortable, or dangerous ECs (Lysaght et al., 1989). However, it has taken several decades of research to establish a broader understanding of the mechanism(s) of action and pertinence of attentional demands to performance across a broad range of ECs (Bourne & Yaroush, 2003; Hancock & Desmond, 2001; Lupien et al., 2007). Attentional research is still evolving. One avenue receiving particular attention is the potential of training to modify both the mechanism of action (i.e., the adverse response process) and the performance effects (e.g., Tang et al., 2015)

Discomfort, anxiety, and fear have long been known to enhance performance at low levels but to cause profoundly detrimental effects on attention and cognition as the levels increase (see Hancock & Desmond, 2001 for a review). Research employing information processing and neuroergonomic theories and methods have advanced understanding of this pattern (Just et al., 2003; Parasuraman & Wilson, 2008; Petersen & Posner, 2012). For example, Bourne and Yaroush (2003) reported finding the inverted-U pattern of effects on detection and noticing and understanding and decisionmaking in a variety of conditions. Hancock and Vasmatzidis (2003) noted that heat related distraction added an incremental cognitive load involving vigilance that left fewer resources available for concurrent tasks. Paulauskas (2015) showed that cold related distraction (vs. hypothermia) affected the levels of neurotransmitters in the brain in both the prefrontal cortex (associated with attention and judgment) and other cortical regions, with detrimental effects on cognition (especially working memory and attention). More recently, Muller et al. (2012) showed that such degradations can persist for up to 1 hour after exposure ceases and physiological measures have returned to baseline levels, which suggests a neurochemical underpinning to the degradation (see Lupien et al., 2007).

The Lupien et al. (2007) and Staal (2004) reviews of the effects of stress on cognition noted that neurological studies have shown that under EC-induced activation, the hypothalamic-pituitary-adrenal axis (the reticular activating system) releases stress hormones into the brain and bloodstream (e.g., cortisol, epinephrine, norepinephrine[2]). Studies have shown that cortisol level follows an inverted-U relationship with exposure, similar to that of performance. When noise, heat, cold, or other ECs are sufficient to activate the reticular activating system it can interrupt attention and memory processes.

Beyond cognitive impacts, research has also made progress in demonstrating and clarifying the mechanisms by which a high level of arousal interferes with performance involving complex skills, fine muscle movements, coordination, and steadiness, as well as general concentration (Dovan, 2013; Paul, 2012).

1.3.3 Discovery of New Retinal Receptors

The identification of fundamentally new sensation receptors is remarkable at the current point in the history of biological science—the physiology of sensory systems has long appeared highly settled. Nevertheless, research on structures previously thought to be well understood has led to new insights into human sensation and perception. The discovery of novel retinal receptors, sensitive to blue/green light, may be the most important advance regarding the impacts of ECs on human visual performance and arousal (Berson, 2003; Brainard et al., 2001; Zele et al., 2011). This subclass of retinal-ganglion cells previously was only thought to serve in combining multiple rod and cone information and thereby provide opponent processing involved in color perception. However, recent study has demonstrated that these receptors provide input affecting both visual sensitivity and the human sleep arousal cycle. These intrinsically photosensitive retinal receptors use blue/green light to provide the brain with the major time-giver (zeitgeber) for setting the circadian system. Their existence helps explain the effect light has on arousal and thus performance, which was previously poorly understood.

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[2] The well-established fight-or-flight response to stress and danger is produced via epinephrine and/or norepinephrine

1.4 Structure of this Volume

The body of this volume reviews the performance effects of 11 ECs associated with external flooding events in the following Chapters:

1. Introduction
2. Heat
3. Cold
4. Noise
5. Vibration
6. Lighting
7. Humidity
8. Wind
9. Precipitation
10. Standing and Moving Water
11. Ice and Snowpack
12. Lightning

The review of the research literature on each EC employs a common topical structure organized by these subsections:

- Introduction,
- Attributes and Units of Measurement,
- Time Variation,
- Mechanisms of Action,
- Effects on Performance,
- Potential Mitigation Measures and Their Effectiveness,
- Interactions with Other ECs, and
- Summary of Effects on Performance.

This topical structure, as suggested by its components, was designed to facilitate a broad understanding of the nature and performance implications of respective individual ECs (and interactions with other co-occurring ECs). These, and literature derived guidelines, point to means for practicable use of the reviewed information for estimations of effects, recommended limits (primarily focused on safety), and potential mitigation measures. A summary (Chapter 13) concludes the volume with a summary of the literature and includes a graphical overview of the ECs' impacts across performance demands.

2 HEAT

2.1 Introduction

Workers at NPPs may be exposed to varying levels of heat when performing duties indoors or outdoors, where exposed to environmental conditions. Exposure to elevated temperatures (heat) is especially likely during the warmest months of the year in U.S. subtropical and temperate zones, while preparing for or recovering from tropical storms, or working in confined spaces near heat generating equipment. In physical terms, heat is defined as the form of energy produced by the vibration of molecules. Heat also is experienced subjectively by individuals. This subjective experience can vary depending on factors other than air temperature as it is measured by a standard thermometer. External factors such as radiant temperature, humidity, and air movement, as well as personal factors such as current metabolic heat production, perspiration, and the insulating effects of clothing, can cause heat perception to be higher or lower than the current air temperature.

The effects of heat on human physiology are among the most studied of the ECs, because it is a common environmental stressor for soldiers, construction workers, and other manual laborers. This commonality has prompted a wide range of research addressing both the physiological and subjective effects. The subjective experience of heat has been studied most often with respect to heat's effects on human performance. Across physiological and performance studies, heat has been measured in over 30 different ways, each considering one or more factors in addition to air temperature. The most commonly accepted approach for characterizing the external environment is the Wet Bulb Globe Temperature (WBGT), which takes into account temperature, humidity, air movement, and solar radiation (from both visible and infrared light).

Heat adversely affects work involving gross physical exertion. Heat has also shown fairly distinct effects on “simple mental tasks” (e.g., arithmetic computations, logical reasoning, memory recall, reaction time, etc.), and on perceptual/motor tasks (e.g., manual tracking, vigilance, etc.). However, these effects tend to occur at different heat ranges. Thermal stress, defined as the physical and psychological reactions to heat stimulus outside the normal human comfort zone, also directly affects some basic sensation and perceptual mechanisms. For example, visual acuity shows a linear decline with physiological signs of thermal stress. Heat, and acclimation to it, also affect the subjective experience of heat, especially “discomfort.”

Figure 2.1 provides an overview of the attributes of heat as well as the extent of research and MA relevance.

2.2 Attributes and Units of Measurement

Heat and its effects are measured in a variety of ways, but air temperature is the most basic measurement used in characterizing the experience of this EC and its effects on human performance. The subjective experience of heat is measured in several ways as well, each considering one or more factors in addition to air temperature. The most widely accepted measure for the heat experience is WBGT, which incorporates air temperature, humidity, air movement, and solar radiation (from both visible and infrared light). Temperature is commonly

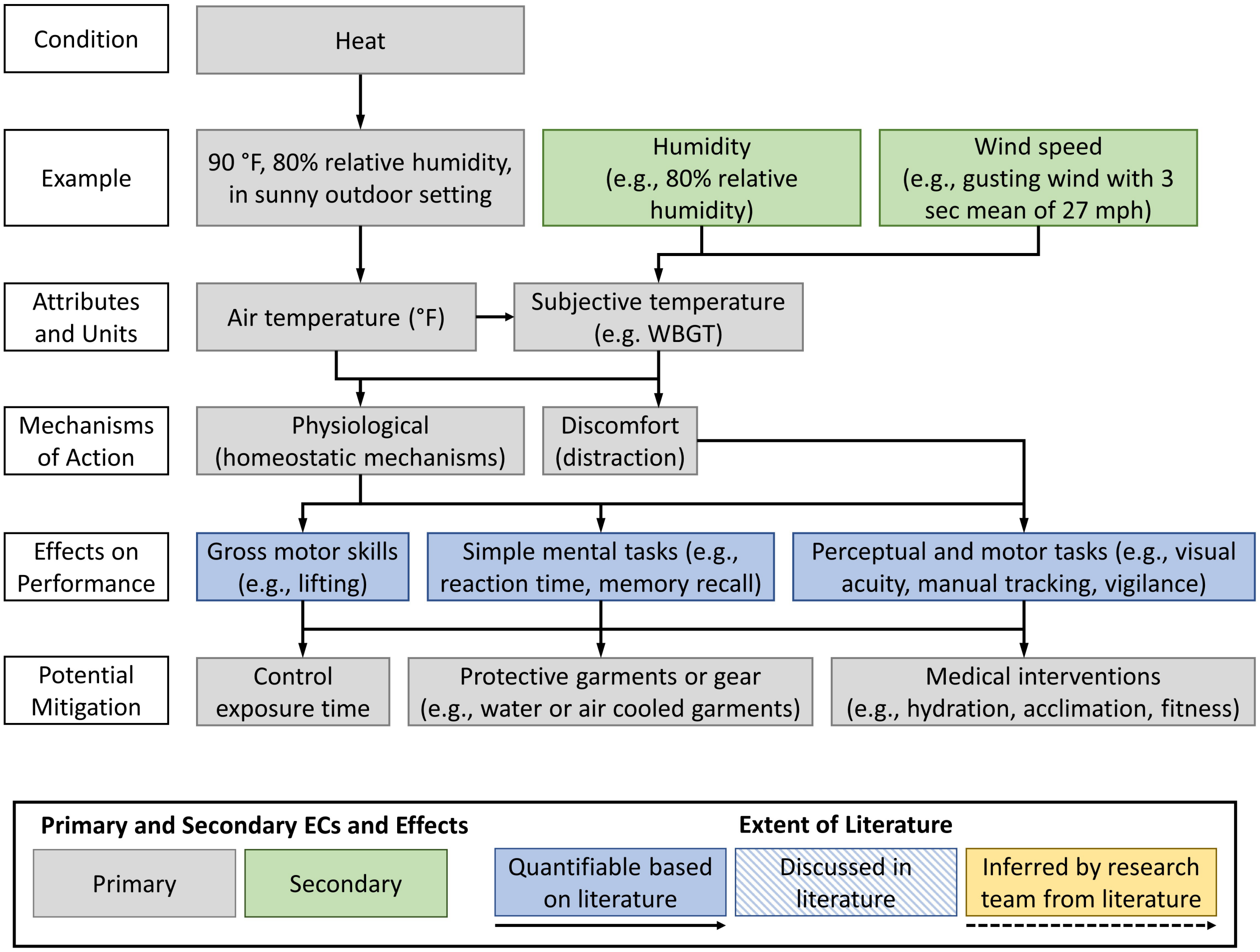

Figure 2.1 Heat effects overview[1]

measured with an analog or digital thermometer, in degrees Celsius (°C) or Fahrenheit (°F)[2]. WBGT is also measured in °C or °F.

$$WBGT = 0.7t_{nwb} + 0.3t_g \tag{2-1}$$

WBGT is calculated for outdoor situations as

$$WBGT = 0.7t_{nwb} + 0.2t_g + 0.1t_g \tag{2-2}$$

Where "wet bulb" t_{nwb} (°C) represents the effects of humidity and air movement and "globe" t_g (°C) represents the effects of air temperature and radiation[3]. The term t_a (°C) represents air

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[1] Only some performance demands are listed here, as others may not be significant for the example condition.

[2] These units are interrelated by the relationship °C = 5/9·(°F–32). Numbers corresponding to both units are presented; the first number reflects that primarily employed in the salient literature and the second a computed approximation of the alternative (most often in parentheses).

[3] Wet bulb and globe temperatures are typically measured using a unified commercially available WBGT apparatus.

temperature for situations involving sunshine (radiant heat), and t_g (°C) represents air velocity and temperature in the absence of sunshine. This is presently the most utilized measure in the research literature, although it has its occasional detractors (e.g., Alfano et al., 2012). The NWS also uses heat index, calculated based on air temperature and humidity (NOAA-NWS, 2014).

2.3 Time Variation of Heat

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to high temperatures. More importantly, because the air temperature during a flood may change, personnel exposure to heat may also be variable in time. In other words, the severity of heat is time dependent and may vary significantly over the duration of execution of a manual action or task.

Figure 2.2 illustrates the dynamic temporal variation in heat during a hypothetical flooding event. In this illustration, three sequential MAs (MA 1, MA 2, and MA 3) are portrayed with relatively short recovery breaks between them. During a prospective or ongoing flooding event, near term heat variations may be predicted via weather reports, and this information may be used in planning work activities to minimize heat stress.

2.4 Mechanisms of Action

The two-major interacting and/or competing mechanisms of action that account for the effects of heat on human performance reflected in the research literature are physiological and psychological. These mechanisms exert their effects through a mixture of changes in body temperature, arousal, discomfort, and attention.

2.4.1 Physiological

The human body seeks to maintain a constant internal body temperature of approximately 98.6 °F (37 °C) through homeostatic mechanisms. Core body temperature and the temperature of the head are used as measures of one of the physiological effects of environmental heat on the body and the mechanisms by which it affects performance. Head temperature predicts cognitive performance deficits better than core temperature.

The thermoregulatory center in the hypothalamus of the brain receives inputs from thermoreceptors in the hypothalamus (for monitoring the temperature of the blood) and in the skin (for monitoring temperature external to the human body). The mechanisms used to maintain a constant core temperature are evaporation (i.e., sweating), radiation (i.e., skin vasodilation), and breathing (i.e., exhalation). Sweating increases thirst and can cause dehydration if fluids and electrolytes are not adequately replaced. If the homeostatic mechanisms are overwhelmed, the body stores heat and internal temperatures rise. Both dehydration and increased body heat have a variety of effects on the individual’s physiology, health, and performance.

The human body can ameliorate the physiological effects of heat exposure by acclimation. Within certain limits, 7 to 14 days of consistent but controlled exposure to heat prompts the body thermal equilibrium. When these heat loss mechanisms are active, the temperature of the skin surface increases (with facial flushing), providing an indicator that this process is under way (in contrast to facial pallor). Heat sources external to the body can disrupt this equilibrium if sufficiently extreme in amount and duration, thereby overwhelming these processes and

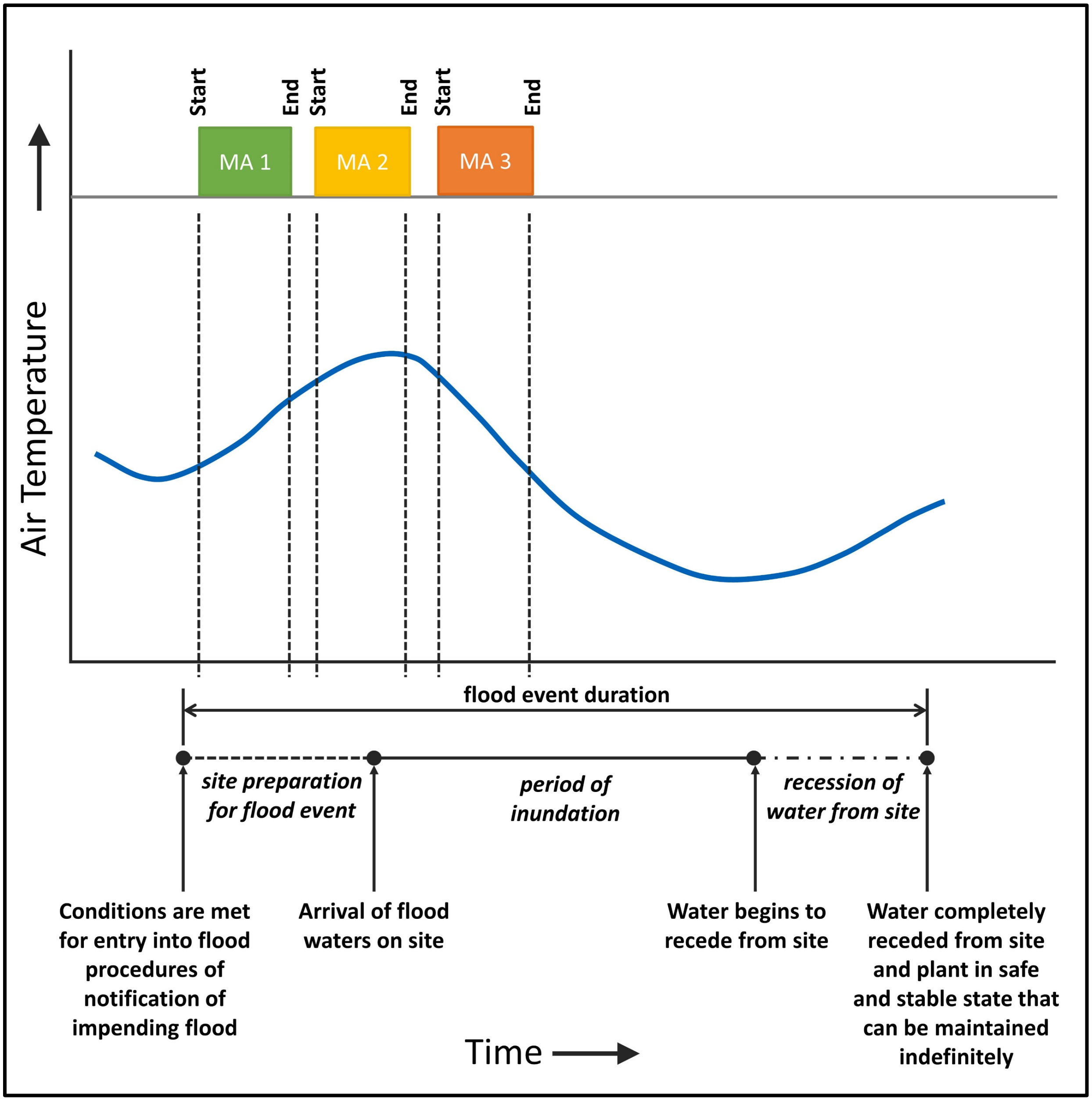

Figure 2.2 An illustration of high air temperature variation during an example of a hypothetical flooding event (Flood timeline in bottom panel from JLD-ISG-2012-05, USNRC, 2012)

contrast to facial pallor). Heat sources external to the body can disrupt this equilibrium if sufficiently extreme in amount and duration, thereby overwhelming these processes and causing increased bodily heat retention and raising the core body temperature beyond 98.6 °F (37 °C). In addition, the specialized protective clothing sometimes required for the types of tasks under consideration can interfere with evaporative heat loss, thereby causing or exacerbating heat retention.

As heat stress increases, the circulatory system diverts warm blood to the body's surface until up to 15 to 25 percent of the cardiac output passes through the skin. This necessarily reduces blood flow, and therefore oxygenation, to deep tissues (e.g., the digestive system), the musculature, and even the brain. The effects of acute hypoxia (i.e., deficiency in the amount of oxygen reaching the tissues) range from fatigue (Virués-Ortega et al., 2004) to neural damage to the brain (Bjursten et al., 2010). Further, the cooling effect of sweat evaporation comes at the cost of depleting fluid reserves, which can cause dehydration and a relative loss of electrolytes. This process is responsible for heat cramps and heat exhaustion. Both dehydration and muscular hypoxia have shown clear adverse effects on strength and physical exertion. The cognitive effects of dehydration are also well established, progressing from headaches and blurred vision to, in their extreme, speech loss, delirium, and loss of consciousness.

Bodily hyperthermia itself can cause fundamental disruption and damage to the brain, especially when the condition is extreme. The deleterious effects of heat on the brain itself, from the individual neuron level to that of region-specific orchestrated patterns of activity, have long been recognized (e.g., Kiyatkin, 2010). Neural tissue becomes damaged at deep body temperatures of 104 °F (41 °C) or above. When this hyperthermia cannot be abated quickly, workers may suffer from heat stroke, developing headaches, myasthenia (muscle weakness), confusion, and ultimately, loss of consciousness and even death.

2.4.2 Psychological

Compared to skin and head temperature, core temperature tends to lag in relationship to performance decrements. Many studies demonstrate that short exposures to heat induce performance decrements before homeostatic mechanisms can produce significant perturbations in core temperature (e.g., Ramsey & Kwon, 1992)[4]. Thus, researchers have sought to clarify the other mechanisms that cause heat effects on performance.

The state in which homeostatic mechanisms easily maintain the balance between heat loss and heat retention has been termed thermal comfort (Bradshaw, 2010). As this balance is lost, and heat retention can no longer balance heat loss, the individual enters a state of heat stress. Some authors consider heat stress to constitute an incremental cognitive load involving vigilance and a mental assessment process of the perceived demand created by the situation, perceived ability to cope, and perceptions of the importance of being able to cope with the demand. This incremental cognitive load places additional demands on limited resource systems, leaving fewer resources available for concurrent tasks (e.g., Hancock & Vasmatzidis, 2003; Lupien et al., 2007; McGrath, 1970; Staal, 2004). The incremental cognitive load from heat stress is thought to explain some of the differences in the patterns of heat effects for simple cognitive tasks and more complex, effortful ones, as discussed below. Thus, at least for temperatures below those that damage health (as discussed in Section 2.4.1) and/or for moderate exposure times, the mechanism for heat effects on cognitive tasks may be driven by the consumption of effortful attentive and/or central executive processes, in addition to or instead of heat's effects on physiology.

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[4] Figure 2.3 portrays effects in terms of WBGT (vs. core temperatures) as (1) this is highly related to group subjective responses in the short term and to group average core temperatures in the longer term; (2) this and exposure times are frequently the only exposure data available for summarization of effects; and (3) work planning may only be conducted in terms of WBGT and exposures levels (individual differences being unknown).

2.5 Effects on Performance

Performing physically demanding work in excess heat increases internal heat production and raises the core temperature of the body, the heart rate, and oxygen consumption, and will alter blood chemistry. It can lead to growing discomfort, loss of physical strength and endurance, impaired cognitive performance, and, if not addressed, exhaustion, disorientation, and collapse.

2.5.1 Physical Strength and Endurance

Studies have demonstrated heat effects on the performance of tasks requiring physical endurance, such as repetitive lifting (Maresh et al., 2014) vigorous cardiovascular exercise (González-Alonso et al., 1999), and construction work (Mohamed & Srinavin, 2002). The experience of occupational heat stress, whether related to climate or proximity to heat generating equipment, is strongly associated with workplace accidents and injuries (Ramsey et al., 1983). Perspiration produced in response to heat can contribute to slips and falls.

2.5.2 Cognitive Performance

Of the ECs addressed in this report, the effects of heat on cognitive task performance have probably received the most research attention over the last 50 years. Nevertheless, authors have continued to argue that questions concerning the effects of heat on human performance remain unresolved (e.g., Gaoua, 2010; Grether, 1973; Kobrick & Fine, 1983; Ramsey & Morrissey, 1978; Ramsey, 1995). The non-equivalence of key variables and differences in subject populations across studies are cited as the main reasons for disparate research results (Chase et al., 2005). Key variables also include task difficulty differences (Chase et al., 2005), degree and duration of exposure, task familiarity and training, and experimental methodologies (Hancock & Vasmatzidis, 2003; O'Brien et al., 2007). Some cognitive effects of heat exposure, for example, are significantly moderated by the extent of training, but many studies do not clearly describe the degree of training or even account for training and familiarity effects in repeated measures.[5] Gaoua (2010) reprised these and other issues that tend to make aggregation of findings across studies inconclusive.

Ramsey (1995), in his classical attempt to clarify the underlying causes of conflicting research results, separated the effects of heat on cognitive performance by whether the task was simple or complex. Generally speaking, simple cognitive tasks were defined as those requiring only low effort perceptual or motor skills (e.g., simple reaction time, memory recall). These simple cognitive tasks were found to be less vulnerable to heat stress than more effortful, complex tasks (e.g., a dual task, visual motor tracking, and vigilance). Simple and effortful cognitive tasks also tended to show both onset and asymptote of deleterious effects at different temperatures. Effortful cognitive tasks generally show both earlier onset and earlier asymptote than simple ones, as shown in Figure 2.3. The assertion that a fundamental physiological process may govern the effects on simple mental tasks was supported by evidence that simple mental task

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[5] A related long-term issue in heat and all other environmental performance testing is the instability of task performance during repeated trials (Bittner, Jr. et al., 1986; Echeverria et al., 2002); overtrained tasks represent quite different capabilities than those very infrequently performed (e.g., performed only during a flood or other emergency situation). Overtraining or overlearning is repetition of a skill until it can be performed automatically, freeing attention to focus on other things.

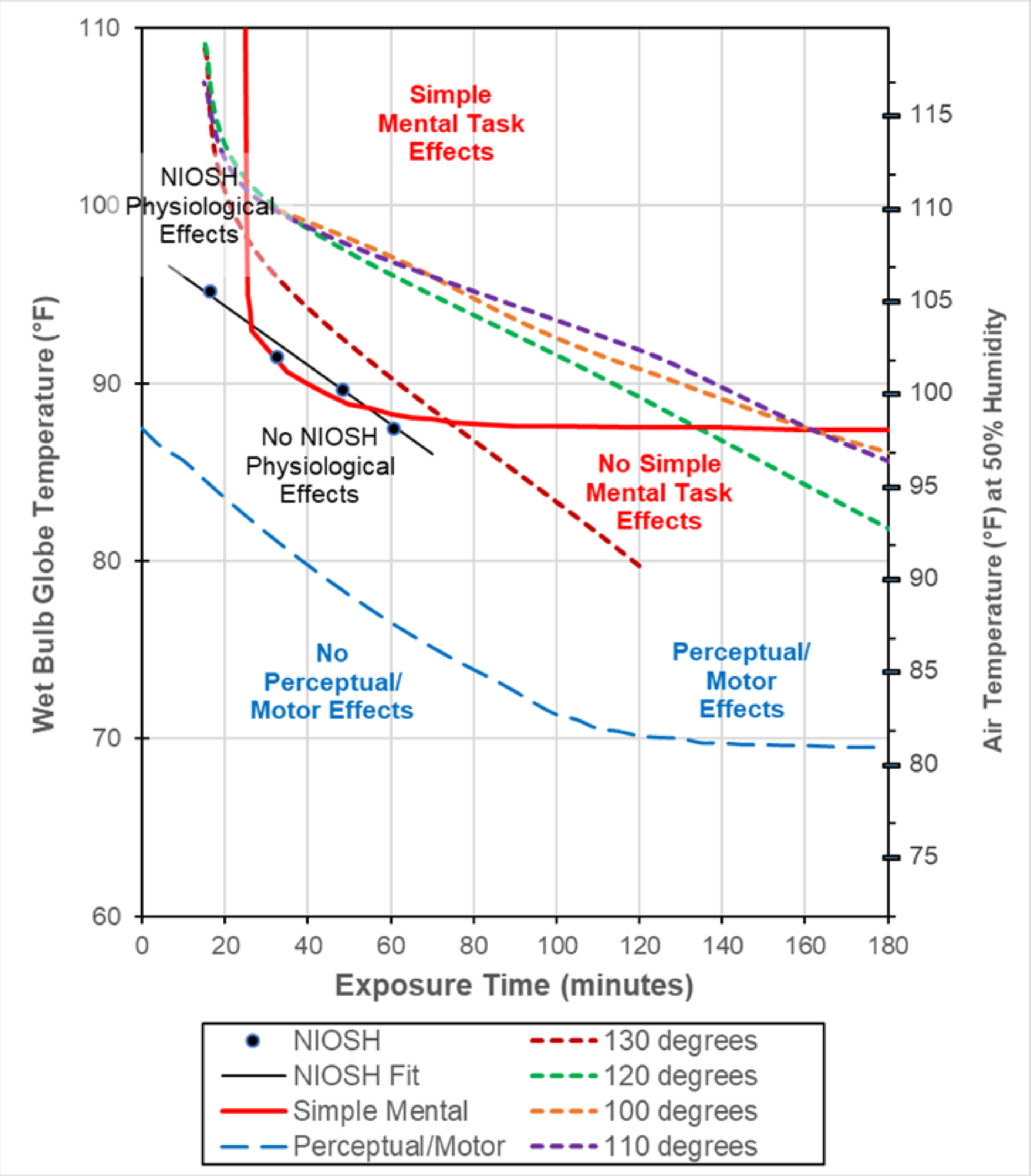

Figure 2.3 WBGT and exposure time effects on physiology and on simple mental and perceptual/motor tasks source. Adapted from Echeverria et al. (1994) and allowable work time for different air temperatures (U.S. Army, 1992 Table L-3).

performance degenerates near the NIOSH threshold for physiological collapse, which is also shown in Figure 2.3.[6]

As also discussed for other ECs, thermal discomfort shows distinct effects on effortful attentive and central executive processes. When experiencing discomfort from heat, subjects report mentally dwelling on the discomfort, thereby taxing limited mental resources. Regarding heat, Gaoua et al. (2012) showed that performance of a working memory task (e.g., a complex cognitive task) was significantly impaired when skin temperature (and not core temperature) increased by 3 °C (~5.4 °F), a condition in which individuals reported a significant increase in discomfort. Further suggesting a discomfort related explanation for these effects, cooling the skin of the head preserves some complex cognitive functions far more quickly than core or brain temperature would be reduced (Gaoua et al., 2012). Heat effects also appear for tasks requiring attention and executive control that were performed under more natural conditions. For example, simulator studies of driving have shown an increase in both missed signals (Wyon et al., 1996) and failure to maintain a safe driving position on the road (Daanen et al., 2003) under moderate heat stress.

2.5.3 Sensation and Perception

There is some evidence that heat stress can cause degradation of basic sensation and perception. As discussed by Echeverria et al. (1994), for example, the majority of studies examining the relationship between heat exposure and vision have concluded that temperatures inducing physiological strain also adversely affect visual acuity.

2.5.4 Recommended Limits

Guidelines in the form of Recommended Alert Limits[7] and Recommended Exposure Limits have been developed to ensure that the health of most workers is not adversely affected by heat. When applying these guidelines, however, professional judgment remains important because individual differences (i.e., task skills, age, gender, and cardiovascular health) and other unaccounted for situational factors (e.g., clothing, caffeine/alcohol intake, etc.) may affect how a particular worker responds to heat exposure (Jacklitsch et al., 2016). For workers outfitted in protective clothing, the appropriate guidelines are those applicable to an environment that is 10°F (~5.6°C) higher (i.e., add 10°F [~5.6°C] to the observed WBGT temperature when applying the guideline to account for reduced heat dissipation caused by the protective clothing) (Jacklitsch et al., 2016).

Jacklitsch et al. (2016) includes NIOSH heat stress Recommended Alert Limits and Recommended Exposure Limits for both nonacclimated and acclimated workers. These criteria consider both work-rest intervals (recognizing that when working for shorter intervals, humans can bear higher temperatures without adverse health effects) and the physical intensity of the work. The NIOSH Recommended Alert Limits and Recommended Exposure Limits were derived using a physiologically based approach primarily focusing on worker safety. Figure 2.4 and

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[6] Ramsey (1995) essentially represents a summary of young, nonacclimatized subjects performing sedentary tasks. For comparison between simple tasks and underlying physiological limits, the “NIOSH Physiological Limit” portrayed in this figure was earlier derived in NUREG/CR-5680 by recasting the estimated NIOSH exposure limits for sedentary, nonacclimatized workers (later shown in Figure 2.4). The NIOSH limits shown here are estimated to provide for 95 percent protection of workers.

[7] Recommended Alert Limits are NIOSH recommended heat stress alert limits for nonacclimatized workers.

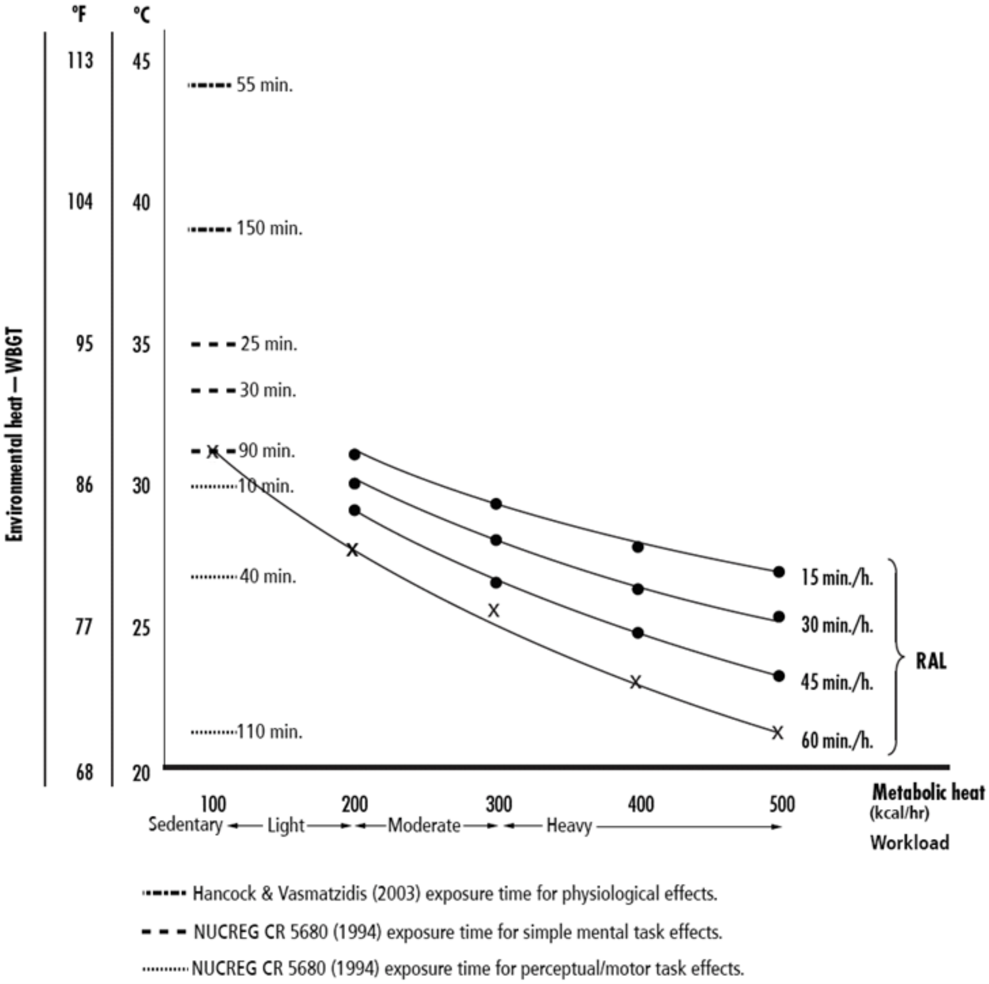

Figure 2.4 Recommended heat stress exposure limits by recommended alert limits (RALs). Values shown are for a "standard man" of 70 kg (154 lb) body weight and 1.8 m2 (19.4 ft^2) body surface. The "standard man" is used to normalize the data from the variability found in human beings.

Figure 2.5 graphically show the conditions under which a worker's total heat exposure is within the acceptable combinations of metabolic and environmental heat limits for work tasks that cover a wide range of physical effort. Specifically, they show Recommended Alert Limits for 60-, 45-, 30-, and 15-minute work periods for acclimated and nonacclimated workers. Below each curve, 95 percent of the general population of manual workers should be able to successfully maintain a safe thermal homeostasis. Sharply contrasting with these basic NIOSH limits are physiological collapse temperatures shown in the left boundary of the figure as derived by Hancock and Vasmitizidis (2003). Their limit of ~102°F for 150 minutes exceeds the NIOSH ~92°F limit for acclimated sedentary workers. This difference points to significant population, analytic, and/or criteria differences, and caution is recommended when considering their research described later in the next chapter.

Hancock and Vasmatzidis (2003) present a framework for setting heat performance limits for different types of cognitive tasks that contrasts with earlier research (as noted immediately

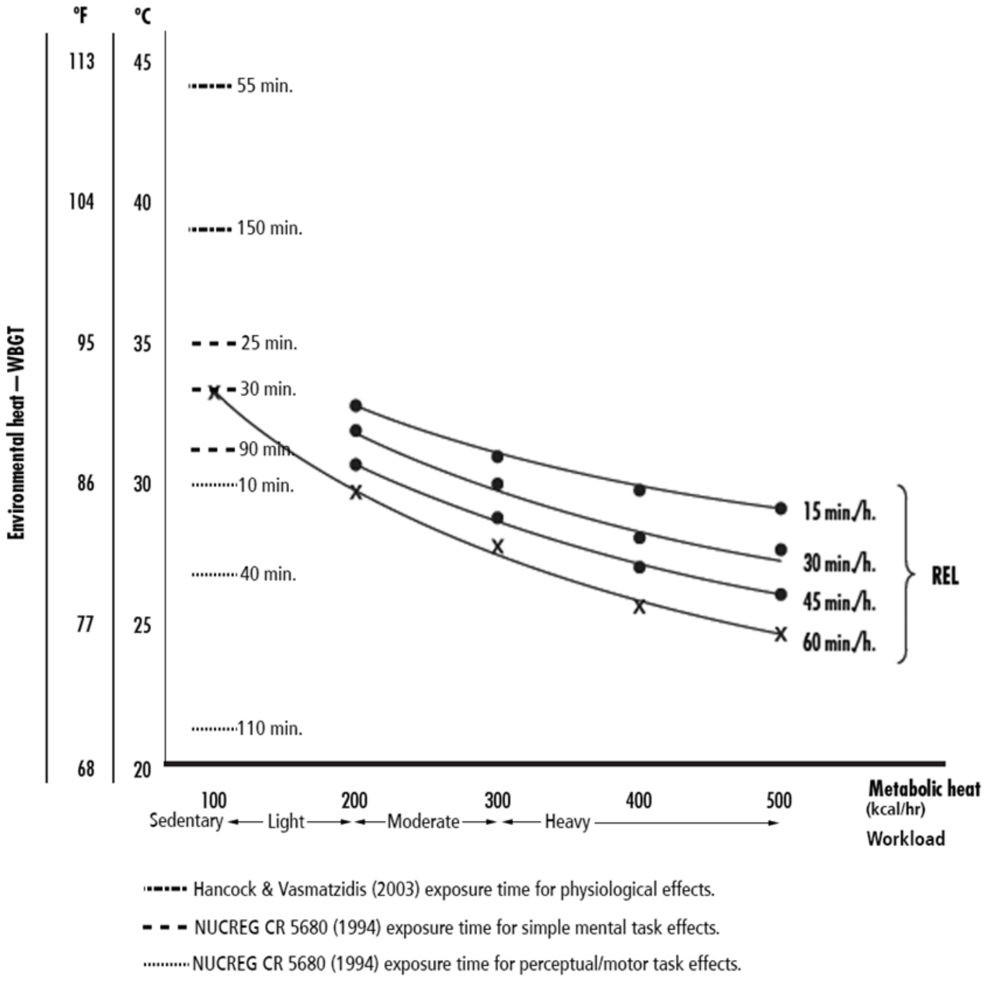

Figure 2.5 Recommended heat stress exposure limits by recommended exposure limits (RELs). Values shown are for a "standard man" of 70 kg (154 lb) body weight and 1.8 m2 (19.4 ft^2) body surface. The "standard man" is used to normalize the data from the variability found in human beings.

The parallel lines in Figure 2.6 are described by the equation:

$$WBGT = a - 5.435 \log_e T \qquad (2\text{-}3)$$

where *T* is the exposure duration in minutes, *WBGT* is the wet bulb globe temperature, and *a* represents the intercept values reflecting the attentional involvement required for each task category plotted. Table 2.1 is a tabulated version of these values.

As noted earlier, the Hancock and Vasmatzidis (2003) recommendations for significant EC performance effects are also overlaid in Figure 2.4 and Figure 2.5. The range in these figures is remarkably higher than the NIOSH safety recommendations of Jacklitsch et al. (2016). Although above). Their approach is nominally associated with a dynamic rise in deep body temperature.

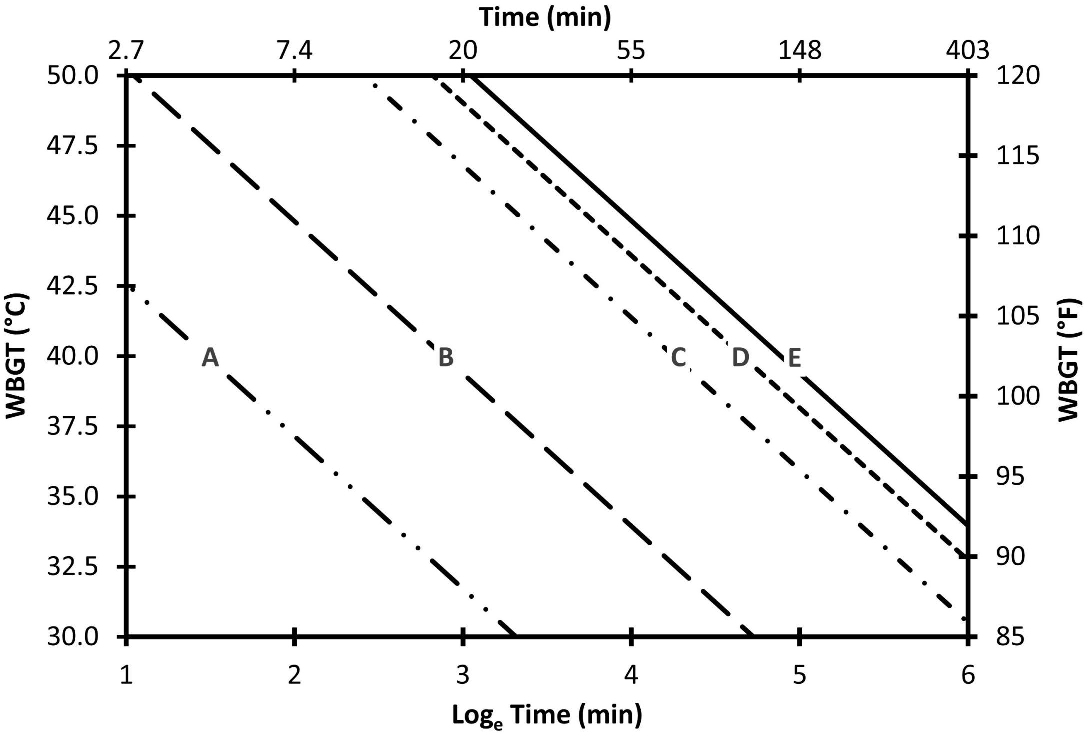

Figure 2.6 WBGT performance limits for various tasks (Hancock & Vasmatzidis, 2003). Lines denote vigilance (A), dual-task (B), tracking (C), and simple mental (D); line E represents the physiological tolerance limit.

Table 2.1 Intercept values for task performance limits in heat

Curve	Task Type	Empirical Intercept for ET* Limits	Tolerance Adjusted Intercept for ET Limits	Empirical Intercept for WBGT^ Limits	Tolerance Adjusted Intercept for WBGT Limits	Dynamic Rise in Deep Body Temperature (°C)
A	Vigilance	42.82	41.00	48.02	45.00	0.055
B	Dual Task	48.59	47.00	55.68	54.00	0.22
C	Tracking	53.96	53.00	63.11	62.50	0.88
D	Simple Mental	55.81	54.00	65.33	64.00	1.33
E	Physiological Tolerance	57.06	55.00	66.56	65.00	1.67

Source: Hancock and Vasmatzidis (2003)
** ET is effective temperature; ^ WBGT is the wet bulb globe temperature*

presented by Hancock and Vasmatzidis (2003) was based on the extreme environments in which exceptional soldier, pilot, and/or astronaut populations might be required to perform. Though the Hancock and Vasmatzidis (2003) recommendations may be used, the NIOSH ranges are arguably more conservative for ensuring worker safety during flooding events.

2.6 Potential Mitigation Measures and Their Effectiveness

The key to mitigating the effects of heat on performance is to provide ways for workers to maintain equilibrium between heat production and heat loss, for example by reducing metabolic heat production, lowering the WBGT, or increasing heat loss. The following mitigation approaches are recommended by Echeverria et al. (1994):

- If feasible, use engineering approaches to mitigate heat effects. This is generally the preferred approach. These modifications should take into account the level of physical exertion required by the tasks being performed and the relative acclimation of those performing the work, with exposure time and work rest schedule guided by the recommended limits shown in Figure 2.4 and Figure 2.5. Increase worker capacity to achieve heat loss without dehydration or electrolyte depletion by maintaining a hydration schedule and providing air movement. This will help avoid dehydration related performance decrements and negative health effects.
- Improve acclimation and physical fitness before exposure. Improving general worker physical fitness through fitness programs can improve the coping abilities of the workforce as a whole. Within certain limits, after 7 to 14 days of consistent but controlled exposure to heat (Armstrong & Stoppani, 2011; Moseley, 1994), the body can acclimate to the heat, and homeostatic mechanisms can again maintain homeostasis. This may ameliorate some of the effects on performance; however, it is important to remember acclimation does not erase performance decrements. Although acclimated workers may be at lower risk for heat
- related illness, they cannot necessarily work as effectively in high temperatures as they can at more comfortable ones.
- Reduce exposure to external sources of heat and provide cooling through protective garments, such as water-cooled garments, air cooled garments, wetted overgarments, and ice packet vests. Care should be taken with garments involving ice because they can interfere with normal physiologic functions and workers' performance (White & Hodous, 1987). During exercise or work in the heat, specific cooling of the head may protect the brain, which contains the most heat susceptible nervous tissue, from damage.
- NIOSH may be consulted for a contemporary amplification on the mitigation approaches outlined above.

2.7 Interactions of Heat with Other Environmental Conditions

WBGT includes the heat related impacts of concurrently occurring humidity and wind. In addition to humidity and wind, heat also may occur concurrently with standing and moving water and precipitation during floods and tropical storms, as well as with vibration and noise (e.g., when heavy equipment is in use).

2.8 Summary of Research on Heat Impacts

The state of the literature addressing the effects of heat on performance demands can be summarized as shown in Table 2.2.

Table 2.2 Heat effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	2	(c)(d)
Sensation and visual recognition	2	(c)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	2,3,4	(c)(d)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, evaluating/selecting options	3,4	(c)(d)
Action		
Fine motor skills - discrete & motor continuous, manual dexterity	3	(c)
Gross motor skills – heavy and light	2	(a)
Other neurophysiological functions	2	(b)
Teamwork		
Reading and writing	4	(c)(d)(e)
Oral face-to-face and electronic communication	2	(c)(d)
Cooperation, crew interaction, and command and control	4	(c)(d)

Assumptions and Limitations of Applicability

(a) *Several identified studies demonstrate quantitative effects on tasks requiring gross motor skills, such as box lifting, cardiovascular exercise, and construction work. However, this quantitative information has not been united in a way that allows one to predict the degree to which gross motor skills in general could be affected at different WBGTs/exposure times.*

(b) *When prolonged exposure to heat causes hyperthermia, neurophysiologic damage is observed when deep body temperatures reach 104 °F (41 °C) or above. At the individual level, body composition, age, and fitness level (among other individual differences variables) can determine speed and susceptibility to hyperthermia.*

(c) *"Simple" cognitive tasks requiring little conscious effort tend to show effects at the approximate heat levels suggested by NIOSH's Recommended Exposure Limits. This may include tasks such as acuity, recognition memory, perception, sensation, and visual recognition. Given that perception is affected, most other tasks "downstream" in cognitive information processing will also be affected.*

(d) *"Complex" cognitive tasks, those requiring conscious effort, show effects at much lower levels of heat (see Figure 2.3), with instantaneous effects beginning at 88oF WBGT, which asymptote as low as 70oF after around 120 minutes of exposure. This may include tasks requiring directed and sustained attention, effortful memory recall, vigilance, task switching, and all effortful higher cognition and meta-cognition processes, such as evaluating, hypothesizing, cooperation, etc.*

(e) *Purely mechanical portion of writing task is likely to respond similarly to expected fine motor skills here.*

Level of Information Categories (1 to 4)

(1) *Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.*

(2) *Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.*

(3) *Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.*

(4) *No information (a gap).*

3 COLD

3.1 Introduction

Outdoor workers at NPPs can be exposed to cold air and water temperatures, especially during the winter in humid continental or subarctic climate zones. Control room workers and maintenance personnel can also occasionally be exposed to cold air temperatures inside buildings. The effects of cold air temperatures on workers are exacerbated by air movement and/or moisture. These both intensify the subjective experience of cold and serve to wick heat away from the body considerably more efficiently than still air and dryness. Direct contact with cold materials can also wick heat away from the body.

Exposure to cold temperatures can overwhelm the body's ability to maintain thermal balance and cause cold stress. Hypothermia occurs when cold stress produces a drop in the body's core temperature. Hypothermia can result in clumsiness and confusion and result in physical and mental errors. As the hypothermic condition worsens, respiration slows, starving the brain and other tissues of oxygen, making errors even more likely. Hypothermia can be fatal in its extremes; thus, strict monitoring and a system of controlled warming breaks are needed to ensure that workers do not become hypothermic when working in cold environments.
There is considerable evidence that exposure to cold also affects worker performance before individuals becomes hypothermic. Most straightforward are cold's effects on manual dexterity, tactile discrimination, and strength, which appear to be due to physiological causes (e.g., thickening of the synovial fluid within the joints, cold rendering the sensory apparatus inoperable (numbness), as well as nerve conduction speed reductions).

The evidence for cognitive deficits due to pre-hypothermic cold exposure tends to be strongest for memory, including short term retention and recall and working memory (arguably due in part to discomfort and/or distraction, much as for heat). The research literature shows mixed results for other cognitive abilities, including reaction time, attention and vigilance tasks, reasoning, and mathematics tasks. There is some evidence that cognitive deficits can persist for as much as an hour after cold exposure ceases, which should be considered when scheduling post-warming break tasks that are essential and have heavy cognitive requirements.

Figure 3.1 provides an overview of cold attributes as well as their literature support levels and MA relevance.

3.2 Attributes and Units of Measurement

Temperature is a measure of the degree of hotness or coldness of an object or body. Specifically, temperature is a measure of the average kinetic energy of the particles in an object. It is typically expressed either as degrees Fahrenheit (°F) or as degrees Celsius (°C).[1] The temperature of both air and water are measured with thermometers.

A cold environment has been arbitrarily designated as one in which the air temperature is below 10 °C (50 °F) for a shirt sleeved worker (i.e., wearing a shirt but no jacket (Cold Environmental, n.d.). However, the functional perception and impact of cold are dependent on a negative heat

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[1] These units are interrelated by the relationship °C = 5/9 (°F -32). Throughout the report numbers corresponding to both units are presented, with the first being that primarily employed in the salient literature and the second a computed approximation of the alternative (most often in parentheses).

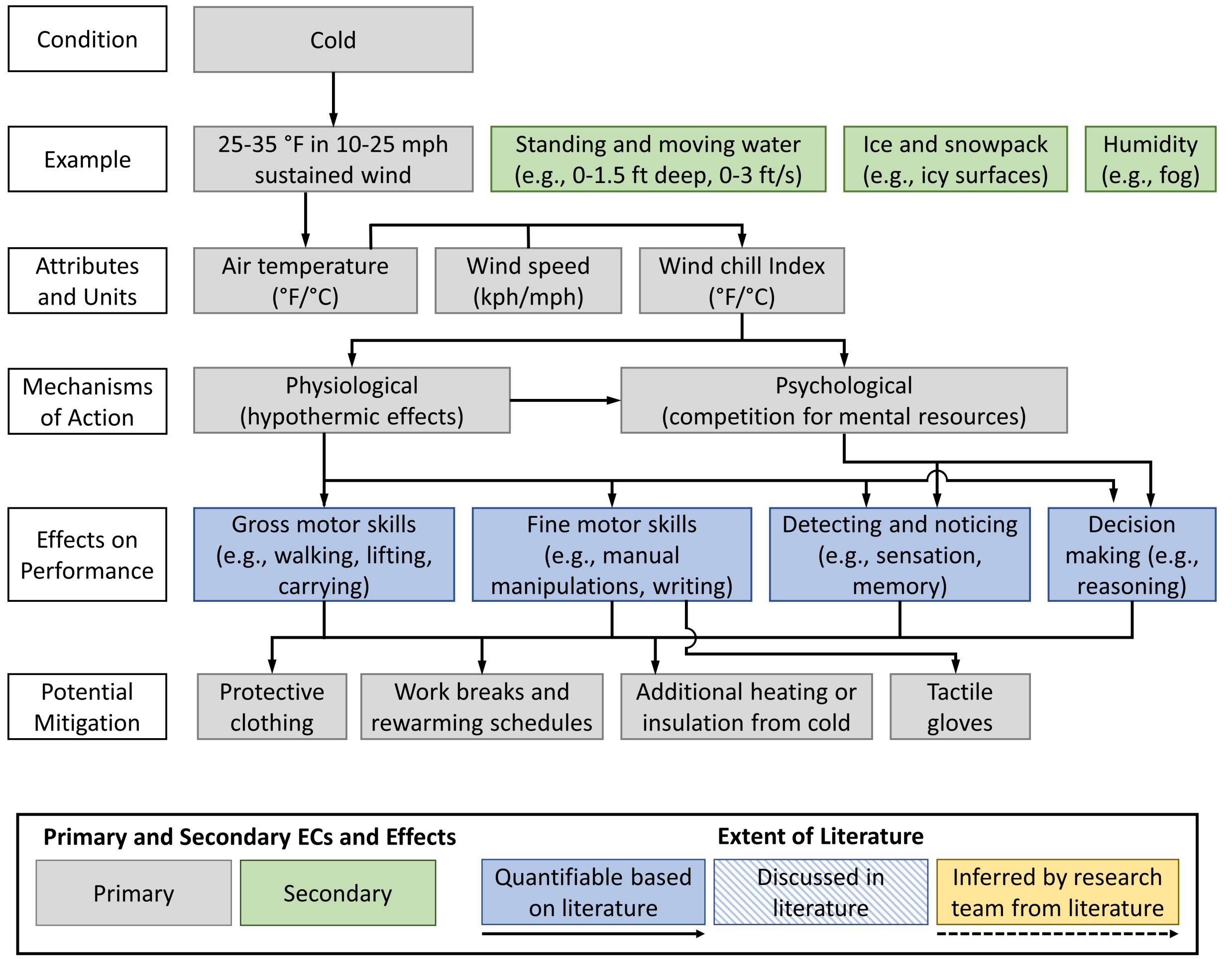

Figure 3.1 Cold effects overview[2]

balance between the worker and the environment (e.g., an overdressed worker could be hot at the same temperature a normally dressed worker would be comfortable). Cold soaked objects are objects that have relatively low heat energy with which workers might come into contact (e.g., metal tools or handrails exposed to low temperatures for long enough to become cold). Exposure to a cold environment or cold soaked objects can reduce the heat energy in portions of a worker's body, especially exposed hands and other extremities.

For most NPP workers, the effects of cold will usually result from the direct attributes of air temperature and movement (albeit exposure to cold soaked objects is always a concern). However, when flooding occurs during winter months, water temperature (and potentially that of other liquids) may also be a source of cold stress.

Under normal circumstances, the homeostatic mechanisms of the human body maintain its internal (core) temperature set point (~98.6 °F/37 °C), as outlined earlier in Section 2.4.1. However, exposure to a cold environment and/or cold soaked (Cold Environmental, n.d.) objects can negatively affect these adaptive mechanisms, making thermal balance difficult to maintain.

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[2] Only some performance demands are listed here, as others may not be significant for the example condition.

When cold is combined with moving air, convection of heat from the skin's surface is especially efficient. This intensifies the subjective experience of cold and rapidly reduces first surface and then core body temperature. The same is true for exposure to cold water, albeit heat transfer from body to water is typically more rapid than to air.

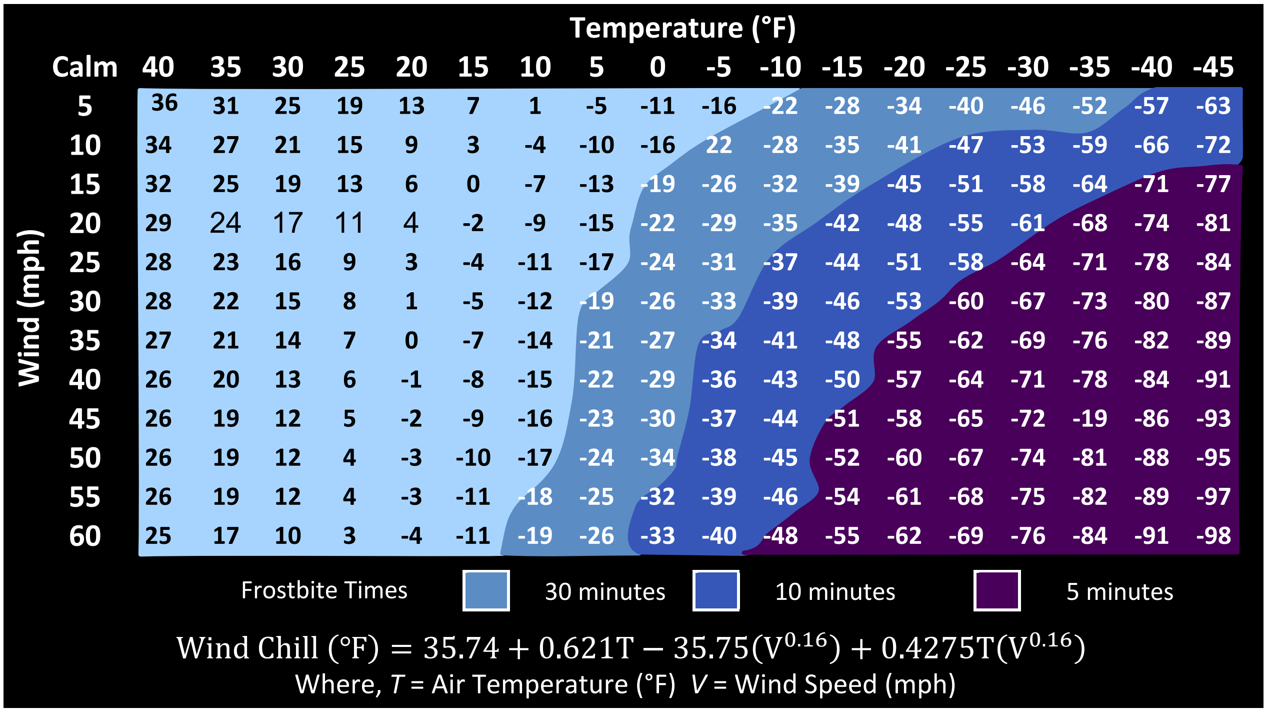
The Wind Chill Index combines measured air temperature with air speed to represent what is felt on exposed skin. As with standard air temperature measurement, this index is measured in °F or °C. Table 3.1 shows the NWS Wind Chill chart, with frostbite zones identified.[3]

3.3 Time Variation of Cold

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to low temperatures. More importantly, because the air temperature during a flood may change, personnel exposure to this EC may also be variable in time. In other words, the severity of an EC is time dependent and may vary significantly over the duration of execution of a manual action or task.

Figure 3.2 illustrates an example of temporal variation in cold during phases of a hypothetical flooding event in which three MAs (MA 1, MA 2, and MA 3) are performed sequentially with intervening recovery breaks. During a prospective or ongoing flooding event, forthcoming cold variations may be predicted via weather reports or impending sunset, and this information can be used in planning work activities to minimize cold effects.

Table 3.1 Time to frost bite based on wind and cold temperature



	Temperature (°F)																	
Wind (mph)	Calm																	
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	29	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	28	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	27	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	26	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-19	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-34	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	26	19	12	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times ▨ 30 minutes ▨ 10 minutes ■ 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.621T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, *T* = Air Temperature (°F) *V* = Wind Speed (mph)

Source: NOAA-NWS, 2017(effective 11/01/01)

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[3] A frostbite zone is a wind chill at which skin, if exposed for a certain duration, will freeze.

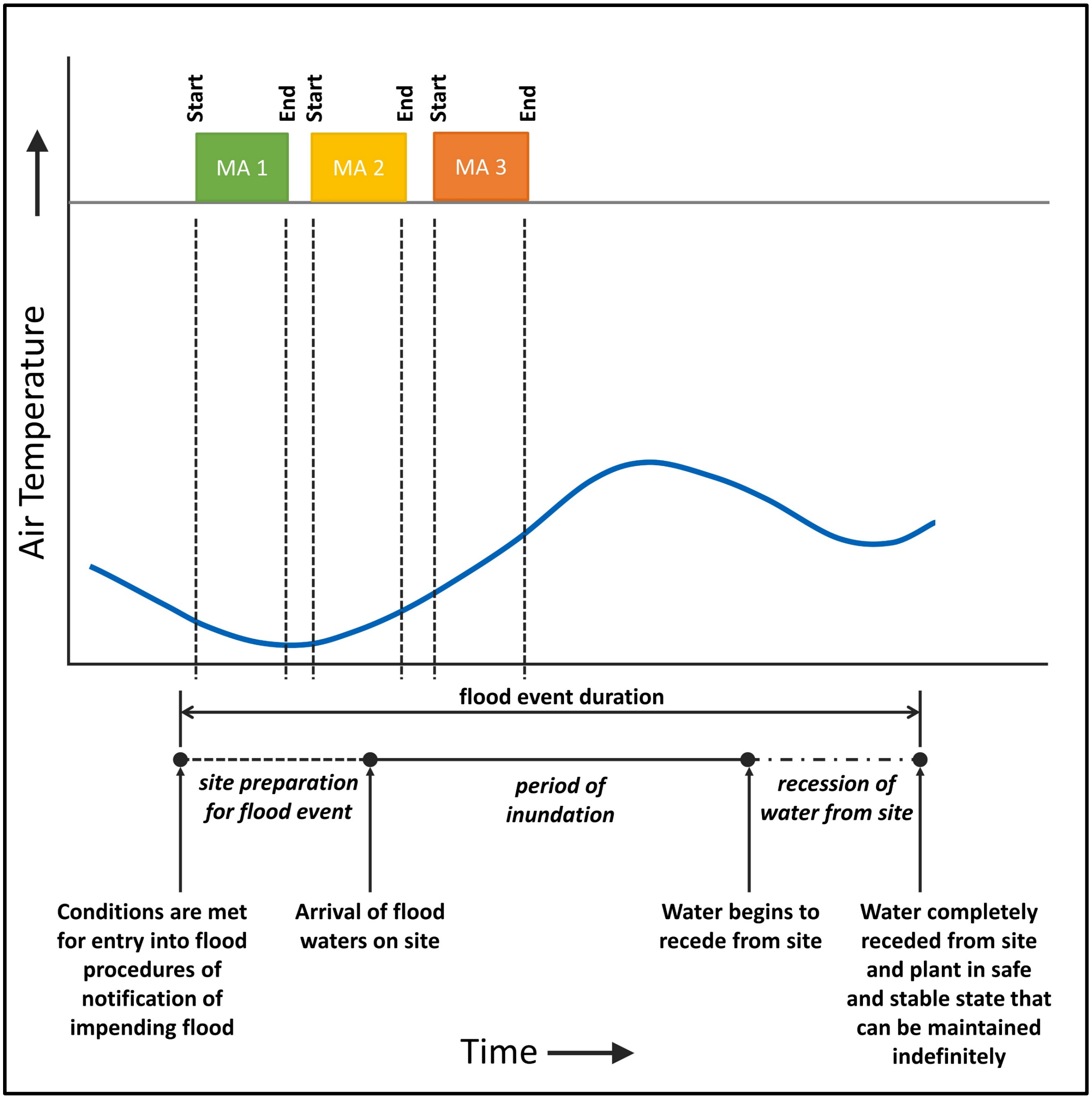

Figure 3.2 An illustration of low air temperature variation during an example of a hypothetical flooding event

3.4 Mechanisms of Action

The mechanisms of action postulated for the effects of cooling (i.e., loss of heat or negative heat storage) on human behavior are similar to those of heat effects, physiological and psychological. Physiological mechanisms, and the resulting physiological effects, tend to be more prominent with longer and more extreme cold exposure. Psychological mechanisms, and the resulting psychological effects, may also be prominent in the early stages of less extreme cold exposure. In fact, the psychological sensation of cold can begin in some contexts and individuals around room temperature (i.e., ~75 °F /24 °C). The subjective experience of pain, and eventually numbness, occurs when actual skin temperatures are reduced to between ~68–61 °F (~20–16 °C). These threshold levels are listed in Table 3.2.

3.4.1 Physiological

Cold stress occurs in reaction to a body's loss of thermal balance. Technically, thermal balance is defined in terms of the amount of heat energy stored in the body as a function of metabolism, convection, radiation, and evaporation. In the following conceptual equation for heat balance, the units of all variables are measures of heat energy per unit of time (i.e., rates or fluxes):

$$S = M + C + R + E \tag{3-1}$$

where S is rate of heat storage, M is metabolic rate, C is convective flux, R is radiative flux, and E is evaporative energy flux (NUREG/CR-5680, Echeverria et al., 1994)[4].

Rate of heat storage (S) may be positive (reflecting increasing energy in storage, which leads to an increasing body temperature), negative (reflecting a decreasing body temperature), or approach zero (reflecting that the body is in thermal balance). The metabolic rate of the body, M, a source of heat energy, is always a positive number. Convective (C) and radiative (R) fluxes may be either positive or negative (depending on whether they are serving as a positive or negative source of heat energy). Evaporation (E) consumes heat energy and therefore is negative (a source of cooling). Thus, thermal balance is defined as any condition in which S is approaching zero. In using this concept to assess the effects of exposure to cold, the assumption is made that the starting temperature of the individual is normal (i.e., at ~98.6 °F). When rate of storage is negative, the adaptive mechanisms of the body are no longer maintaining a stable internal heat level (i.e., at ~98.6 °F), and core temperature will begin to drop. This will lead to one or more of three bodily responses: (1) heat production; (2) heat conservation; and (3) slowing of the nervous system. Both heat production and heat

Table 3.2 Temperatures above which no cold effects occur

Effect of Exposure to Cold		Air Temperature (°F)	Hand Skin Temperature (°F)
General Discomfort		69	75
Effects of Cold on the Hands			
	Skin Sensitivity		75
	Numbness	54	68
	Pain		61
	Finger Discrimination		37
	Grip Strength	14	
Task Performance			
	Fine Manual Tasks	64	55
	Tracking	55	
	Gross Manual Tasks	54	59

Source: NUREG/CR-5680, Echeverria et al., 1994 Table 5-2

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[4] Equation (3-1) is a recasting of the classical human heat balance equation that has been broadly extended in contemporary discussions of cold and heat modeling (Parsons, 2014, pp. 33-34ff).

conservation are attempts by the body to counteract loss of heat to the environment. Slowing of the nervous system is a side effect of the loss of heat and cooling of the body. These responses are typically perceived by workers as “uncomfortable” (Marcus & Belyavin, 1978; Parsons, 2014).

The body can produce additional heat through involuntary shivering and voluntary exercise, both of which increase metabolism, and tend to return the body toward heat storage balance in cold situations (i.e., $S \rightarrow 0$). To conserve heat, blood vessels in the extremities constrict, and those in the body’s core expand. This selectively maintains the heart and other major organs functioning at the expense of extremities, which can negatively affect tactile sensitivity and therefore fine motor skills as well as subject the worker’s extremities to increased risk of frostbite. Finally, the nervous system begins to slow to preserve energy. Prolonged cold exposure and the associated loss of heat ultimately lead to decreased heart and respiration rates and slowed nerve conduction, which affect strength and coordination, thereby adversely affecting gross and fine motor skills. These detrimental effects are compounded by a corresponding reduction of skin, muscle, and joint sensitivity (with increasing joint and muscle stiffness). These effects become especially pronounced as the length and degree of exposure increases.

In summary, sensory and motor task performance tends to diminish progressively under exposure to cold due to:

- decreased sensation as a consequence of skin temperature reduction
- mobility and dexterity reductions due to thickening of the synovial fluid within the joints
- reduction in muscle capacity and effectiveness due to falling muscle temperature
- reductions in nerve conduction speed (and thus sensory and motor abilities) due to nervous system wide slowing.

Beyond these effects are potential complications at the neurochemical level. For example, the endocrine system shows distinct changes due to cold exposure (most typically down regulation, perhaps after a brief up regulation). Cold stress alters the concentration of the catecholamines, dopamine, epinephrine, and norepinephrine in the central nervous system. Concentrations of the glucocorticoid stress hormone cortisol have also been shown to increase in response to intermittent cold exposure (Lupien et al., 2007; Paulauskas et al., 2015). The impacts of these neurochemical alterations remain to be explored, though cold associated down regulation of the levels of neurotransmitters in the prefrontal cortex (associated with attention and judgment) and other cortical regions have been shown to have detrimental effects on cognition, especially working memory and attention (Paulauskas et al., 2015). These alterations might contribute to some disruption of fine and gross motor performance, though they are most directly associated with psychological effects.

3.4.2 Psychological

Past researchers have tended to explain the psychological effects of cold by one of two predominant theories: distraction theory and arousal theory. Distraction theory (e.g., Teichner, 1958) posits that cold stress draws limited attentional resources away from physical and cognitive tasks, interfering with effective and efficient performance (see Enander, 1987). The distracting cold stimulus competes with cognitive tasks for attentional resources, and attention becomes focused on feeling cold rather than the efficient completion of the cognitive aspect of

the task at hand. Experimental findings suggest that as the air temperature drops below ~69 °F (~21 °C), or the temperature of the hands/fingers drops below ~75 °F (~24 °C), mild discomfort may be experienced. According to distraction theory, as this discomfort continues or increases, the probability of performance deficits tends to increase.
Arousal theory, in contrast, posits that cold stress initially increases sensory alertness and arousal, briefly improving both physical and cognitive performance. However, as cold becomes more extreme or persists, it outpaces the compensation provided by this arousal, and performance decrements begin to occur. Both theories fit the preponderance of effects shown in the research literature, but arousal theory additionally explains the performance improvements found by some authors from relatively mild cold stress (e.g., Poulton & Kerslake, 1965; Provins & Bell, 1970; Wilkinson et al., 1964).

Supporting these psychological explanations for cold's effects on performance, several studies suggest that the temperature of extremities (hands and feet) is particularly important to the experience of discomfort. As temperature declines, workers tend to experience the least discomfort just after the point when cold extremities have signaled the brain to engage adaptive heat production and/or conservation (Cabanac, 1969; Chatonnet & Cabanac, 1965; Gagge et al., 1967), but then workers experience increasing discomfort as extremities remain cold over time. Deep body (core) temperature plays a secondary role to that of extremity temperature in discomfort (Cabanac et al., 1969, 1972; Chatonnet & Cabanac, 1965; Marks & Gonzalez, 1974) and tends to correspond more closely with physiological effects.

As discussed above, complementing the distraction- and arousal-theory explanations of cognitive performance are recent findings that cold exposure can affect the levels of neurotransmitters in the brain in both the prefrontal cortex (associated with attention and judgment) and other cortical regions. This has been found to have detrimental effects on cognition, especially working memory and attention (Paulauskas et al., 2015).

3.5 Effects on Performance

3.5.1 Manual Dexterity and Tactile Sensitivity

Local cooling of the hands shows relatively consistent impacts on the performance of tasks that require manual dexterity, tactile discrimination, and strength. Manual dexterity becomes impaired at hand temperatures of ~54–59 °F (~12–15 °C). Tactile sensitivity (due to numbness) becomes impaired at somewhat lower hand temperatures of ~46–50 °F (~8–10 °C) (Enander, 1987). These effects tend to be far more pronounced for fine motor skills tasks, such as those requiring fine rather than gross finger manipulations (Chen et al., 2010; Dusek, 1957). Gross manual tasks, involving interaction with larger objects, begin to suffer at lower air temperatures of ~54 °F (~12 °C) and hand temperatures of ~59 °F (~15 °C).

Almost a century ago, Osborne and Vernon (1922) showed that cold temperatures increase the frequency of industrial accidents. For example, in their sample population of ammunition workers, minor cuts were lowest when temperatures ranged from 69–65 °F (21–18 °C) but increased by 34 percent when temperatures fell below 55 °F (13 °C). This field observation is squarely within the range of experimental manual dexterity degradation in laboratory settings and contemporary field investigations (e.g., Anttonen et al., 2009). Certain fine manual tasks, like picking up small objects, are affected at hand temperatures of 55 °F (13 °C), presumably because the attendant numbness does not allow discrimination of small objects from surfaces. It is possible that workers' shivering responses in cold environments may also interact with any direct effects of the cold on performance. Hancock et al. (2007), for example, have suggested that shivering may indeed produce motor effects similar to those caused by vibration.

3.5.2 Muscular Strength

Muscular strength typically begins to deteriorate at higher temperatures than does manual dexterity. Indeed, at skin temperatures in the extremities below ~81 °F (27 °C), reductions in both muscular strength and endurance have been reported (O'Brien et al., 2007). This effect is especially pronounced when individuals are working in cold water (or other liquids). Local cooling of arms and legs can quickly reduce muscle strength and endurance, increasing the risk of sinking and drowning.

3.5.3 Psychology and Cognition

Some authors have demonstrated cognitive effects resulting from prehypothermic cold exposure, but with considerable variability across individuals and studies. In a meta-analysis of studies on temperature exposure effects, Pilcher et al. (2002) concluded that reasoning, learning, and memory tasks were more negatively affected by cold exposure than attention and perceptual tasks.[5]. Whereas, reaction time and mathematical processing tasks showed nearly no effect sizes for the temperature ranges studied (50‑64 °F/10–18 °C, and under 50 °F/10 °C). A number of studies have detected fairly consistent degradations in various memory abilities, including short term memory recall (Coleshaw et al., 1983; Davis et al., 1975; Patil et al., 1995; Thomas et al., 1989) and working memory (Shurtleff et al., 1994; Thomas et al., 1989). However, reasoning tends to show less straightforward results; some studies show a decrement (e.g., Davis et al., 1975) and others show no effect (Baddeley et al., 1975; Coleshaw et al., 1983; Lockhart et al., 2005). A body of other studies have shown cold exposure effects for vigilance tasks (Allan et al., 1974 [below 32 °F/0 °C]; Muller et al., 2012 [below 50 °F/10 °C]), whereas others have shown little effect (Baddeley et al., 1975 [~41 °F/5 °C]; Hancock, 1986 [55 °F/13 °C]; Mackworth, 1950 [<69 °F/21 °C]; Marrao et al., 2005 [11 to 39 °F/-12–4 °C]).

The mixed effects of cold on cognitive performance are considered to be occurring prior to the onset of hypothermic conditions. However, because the onset of hypothermia may be subtle, it is possible that the participants in some of these studies had slipped into hypothermic conditions unbeknownst to the researchers and their performance was degrading as the subject progressed through hypothermia. Some studies (e.g., Muller et al., 2012) have shown that cognitive deficits can persist for as much as 1 hour after cold exposure ceases and the physiological measures of cold stress have returned to baseline (e.g., skin temperatures, thermal sensation).

3.5.4 Recommended Limits

Table 3.3 shows the risk of hypothermia, or hypothermia danger level, at various cold exposure temperatures and durations, as presented by Ramsey (1975). The temperature ranges and effects shown in the table may not hold for every individual, however, because the onset and, phases of hypothermia vary across individuals depending upon age, body size, and other individual differences. Consequently, these guidelines should be applied very conservatively

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[5] A large effect size was found for reasoning, learning, and memory but a small effect size was found for attention and perceptual tasks, per Cohen's d. Cohen's d is an effect size measure frequently used in meta-analyses that indicates the standardized difference between two means (Cohen, 1974; Cohen, 1988).

Table 3.3 Danger levels for risk of hypothermia

Temperature	Danger Level
-23 °F (-31 °C) and above	Little Danger – The maximum danger is a false sense of security, although exposures over 5 hours may be dangerous
-72 °F to -24 °F (-58 °C to -30 °C)	Increasing Danger – Danger of freezing exposed flesh within 1 min
-73 °F (59 °C) and below	Great Danger – Flesh may freeze within 30 s

Source: Ramsey, 1975

Table 3.4 shows the American Conference of Governmental and Industrial Hygienists (ACGIH) threshold limit values (TLVs) for working in cold conditions, based on the prevailing wind speed and air temperature (i.e., the wind chill factor). The assumed work/break schedule includes a 4 h work period with moderate to heavy activity, with normal breaks (i.e., 10-min breaks) taken once every 2 h and an extended break (e.g., lunch, dinner) after 4 h of work. The ACGIH also recommends warm up periods of 10 min at a 72 °F (22 °C) location[6]. The ACGIH TLVs establish a minimum for worker safety to avoid even mild hypothermia. It assumes that workers can regulate their thermal balance by donning and loosening or removing protective clothing as needed to keep warm while avoiding sweating. Sweating is to be avoided because it significantly increases the subsequent potential for hypothermia due to the exacerbating effect moisture has on bodily heat loss.

This ACGIH work schedule applies to any 4-h work period of moderate to heavy work activity, with warmup periods of 10 min in a warm location and with an extended break (e.g., lunch) in a warm location at the end of the 4-hwork period. Table 3.4 applies only if workers are wearing dry clothing and doing moderate-to-heavy work activities. To use the table for light-to-moderate work activities, the recommendation is to move down one line to decrease the maximum work period and increase the number of breaks.

3.6 Potential Mitigation Measures and Their Effectiveness

Potential mitigations for cold temperature effects on NPP worker performance fall into three primary categories: (1) engineering controls, (2) administrative controls, and (3) medical controls. Engineering controls change the environment such that the amount of cold to which the worker is exposed is reduced by either increasing heat flow or insulating the worker from the cold.

Possible engineering interventions include the following:

- Heat the area around the workstation to reduce workers' effective cold exposure. Electric resistance heaters or space heaters can be effective, but require careful placement and safe operation, including proper venting for those that have dangerous emissions (e.g., carbon dioxide, carbon monoxide). In windy areas, such as on a loading dock, radiant heaters, which do not heat the air but only the person who is working in a fixed location, can serve this purpose.

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[6] Note that Muller et al. (2012) showed cognitive deficits can persist up to an hour after a cold stimulus is removed.

Table 3.4 Threshold limit values for cold exposure

THRESHOLD LIMIT VALUES WORK/WARM-UP SCHEDULE FOR FOUR-HOUR SHIFT*											
Air Temp. Sunny Sky		**No Noticeable Wind**		**5 mph Wind**		**10 mph Wind**		**15 mph Wind**		**20 mph Wind**	
°C (approx)	**°F (approx)**	**Max. Work Period**	**No. of Breaks**	**Max. Work Period**	**No. of Breaks**	**Max. Work Period**	**No. of Breaks**	**Max. Work Period**	**No. of Breaks**	**Max. Work Period**	**No. of Breaks**
-26° to -28°	-15° to -19°	(Norm breaks) 1		(Norm breaks) 1		75 min.	2	55 min.	3	40 min.	4
-29° to -31°	-20° to -24°	(Norm breaks) 1		75 min.	2	55 min.	3	40 min.	4	30 min.	5
-32° to -34°	-25° to -29°	75 min.	2	55 min.	3	40 min.	4	30 min.	5	Non-emergency work should cease ↓	
-35° to -37°	-30° to -34°	55 min.	3	40 min.	4	30 min.	5	Non-emergency work should cease ↓			
-38° to -39°	-35° to -39°	40 min.	4	30 min.	5	Non-emergency work should cease ↓					
-40° to -42°	-40° to -44°	30 min.	5	Non-emergency work should cease ↓							
-43° to below	45° to below	Non-emergency work should cease									

Source: American Conference of Governmental and Industrial Hygienists (ACGIH, 2012)

- Erect windbreaks (e.g., hung tarps or even well-placed vehicles) to partially shield workers from wind and help hold in heat that may be being provided by heat lamps or other sources.
- Cover metal tool handles and equipment controls with thermal insulating material to reduce cold transmission to hands (while also providing grip) and design machines and tools so they can be operated without having to remove mittens or gloves.
- Provide warming huts near the work location. Effective warming huts only need to be warmed to 72 °F (22 °C).
- Insulate cold surfaces such as walls, valves, and pipes to raise the radiant temperature felt by the workers.

Administrative controls are introduced to reduce the effects of excess cold on work performance. These controls entail decisions about task assignments: when specific tasks should be done during a work day, who should do them, and the maximum length of exposure time for workers engaged in physical and mental tasks. Examples of administrative controls include the following:

- When possible, schedule outdoor work during warmer seasons or during the warmest part of cold days.
- Assign more workers to jobs exposed to cold to reduce the duration of an individual's cold exposure.
- Require workers to wear appropriate protective clothing to maintain a core temperature of ~97 °F (36 °C) and encourage workers to be vigilant in self-regulating, adding or removing/loosening clothing as necessary, in order to avoid both sweating[7] and becoming too cold.
- Provide protective clothing ensembles whose total clothing thermal insulation (Clo) value is adequate for the temperature. One Clo affords 13 °F (~7 °C) of protection; workers are assumed to be comfortable at 69 °F (19.4 °C). For example, a jacket and insulated pants rated 2 Clo each (4 Clo total for 52 °F/28.6 °C protection) will afford comfort at 17 °F (-8.3 °C) temperature[8]. Clothing suggestions include:
- Jacket and insulated pants rated for the to be exposed temperature.
- Insulated hat, as much heat is lost from the head/neck region (as much as 1/3 of total heat loss).
- Gloves or mittens.
- Warm shoes/boots and socks. Waterproof boots or coverings should be worn to keep feet dry or time in such conditions should be limited.
- Do not allow skin exposure at temperatures below -25 °F (-32 °C).
- At temperatures below 60 °F (15.6 °C), constantly wet feet are subject to trench foot.
- Repeated skin exposure to temperatures between freezing and 60 °F (15.6 °C) can result in chilblains.
- Exposed skin should be covered to prevent skin irritation from cold.
- Help workers who become wet at air temperatures below 36 °F (2 °C) to immediately change into dry clothing and obtain treatment for frostbite.
- Equip workplaces where the temperature may fall below 61 °F (16 °C) with suitable thermometers and anemometers to monitor temperature changes (at least every 4 h for workplaces with temperatures below the freezing point) and wind chill.
- Provide warming and break schedules consistent with the ACGIH recommendations.
- Provide older adults who have circulatory problems with an appropriate combination of extra insulation, additional heat, and/or reduced cold exposure periods.
- Encourage workers to engage in mild to moderate physical activity, either as part of the job at hand or otherwise, to aid metabolic heat production and possibly to distract their attention from the cold sensation.
- Teach workers and supervisors to be mindful of the signs and consequences of frostbite and hypothermia while working in the cold. Signs of frostbite include a prickling sensation on the skin, numbness, and abnormal red or white skin color. The onset of hypothermia

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[7] The amount of metabolic heat necessary to bring sweat on the skin's exposed surface to vaporization temperature can be many times larger in cold temperatures than at room temperature (72 °F/22 °C), which can easily exhaust workers' energy reserves and make hypothermia more likely.

[8] However, exposed skin should be covered to avoid frostbite

may be subtle, but shivering, which is observable, is a cue that an individual may be becoming hypothermic.

- Monitor workers to prevent hypothermic conditions, whose onset may be subtle, and be aware that even when workers are encouraged to take periodic breaks throughout the day to rewarm themselves, cognitive effects may persist. Implement medical controls only under appropriate supervision because careful monitoring is necessary to achieve the desired benefits while minimizing possible adverse effects and costs. Possible medical controls include the following:
- Ingestion of caffeine, most commonly in the form of coffee, which may increase the metabolic rate and provide additional metabolic heat to counter cold exposure.
- Cold acclimation, which can improve workers' ability to cope with low temperatures and wind chill. Some authors have shown cold acclimation can result in reduced vasoconstriction, increased skin temperature, delayed onset of shivering, reduced stress hormone release, and reduced discomfort (see Mäkinen et al., 2006), all of which may mitigate some of the negative effects of cold.
- Some of the cognitive effects of cold exposure may be moderated by overtraining[9] workers on the task (O'Brien et al., 2007). For example, U.S. Army and other military personnel have shown maintenance of normal performance levels for skills from weapon disassembly and/or reassembly and target shooting to vigilance, working memory, and serial addition/ subtraction for individuals performing these tasks under cold exposure conditions (Clarke & Jones, 1962; O'Brien et al., 2007; Oksa et al., 2006). On the one hand this may partially explain the sometimes-equivocal effects in extended repeated measures studies of cold: over time, participants become increasingly overtrained as the study progresses. Likewise, this may also partially explain the equivocal effects of cold observed for various cognitive abilities. No effect or even improvement in cognition have been found in studies where the participants are soldiers, who are specifically overtrained to perform under thermal extremes.

3.7 Interactions of Cold with Other Environmental Conditions

Cold would often be encountered with standing or moving water during winter flooding events. Likewise, precipitation and/or fog and high relative humidity, followed by a drop in air temperature to below 32 °F (0 °C) may lead to ice coatings that reduce ground and tool traction and obscure displays. Vibration, particularly from chainsaws and other powered hand tools, can exacerbate the effects of cold on tactile sensitivity and hand strength in the short term. With extended exposure can also lead to Hand-Arm Vibration Syndrome, with increasingly severe neural, vascular and muscular degeneration as exposure persists (e.g., Heaver et al., 2011).

3.8 Summary of Research on Cold Impacts

The state of knowledge regarding the effects of cold on performance demands is summarized in Table 3.5.

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[9] Overtraining or over-learning is repetition of a skill until it can be performed automatically, leaving the conscious mind available to focus on other things

Table 3.5 Cold effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	2,3	(b)(c)
Sensation and visual recognition	3	(b) (c)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	4	(b) (c) (d)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	2,3	(b) (c)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	2	(a) (b)
Gross motor skills – heavy and light	2	(a)(b)
Other neurophysiological functions	3	(b)
Teamwork		
Reading and writing	3	(b) (c) (e)
Oral face-to-face and electronic communication	4	(b) (c)
Cooperation, crew interaction, and command and control	4	(b) (c)

Assumptions and Limitations of Applicability

(a) Fine motor skills tend to begin to suffer at around hand skin temperatures of 59 °F (15 °C) and gross motor skills begin to suffer at about 54 °F (12 °C), depending on the specific task. However, skin must be exposed to cold for some time before it drops to this temperature.

(b) The ACGIH recommends specific exposure duration limits by temperature and wind speed, with recommendations not to work at certain combinations of temperature and wind speed (Table 3.4).

(c) Supposed "pre-hypothermic" cold exposure seems to have a more pronounced effect on cognitive tasks that might be considered "complex" (e.g., learning, reasoning, memory), than those requiring little directed resources (e.g., perception, "basic" attention [i.e., simple attention capture]).

(d) Among the items in this category, only reasoning seems to have been examined, and shows inconsistent effects at best.

(e) The purely mechanical portion of the writing task is likely to respond similarly to what is expected from fine motor skills here.

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model. No information (a gap).

4 NOISE

4.1 Introduction

Noise, defined as unwanted, unpleasant, or annoying sound, is a common and significant problem in many industrial settings. Noise from NPP turbines and machinery, transport and construction equipment, weather, as well as coworker discussions can all qualify as noise. Exposure to very loud noise or prolonged exposure to loud noise can cause permanent hearing loss as well as stress, apathy, general depression, ischemic heart disease, and hypertension. Noise activates the brain's reticular activating system, the portion of the brain responsible for the "fight-or-flight" response. Consequently, noise can have significant impacts on hearing, general health, and the perceptual, motor, and cognitive components of MAs. Occupational noise has been associated with reduced worker productivity and higher error rates. Some authors hold that the arousal of the reticular activating system accounts for noise's inverted-U effects on performance, where initial stimulation may improve performance, but increased stimulation subsequently leads to a decrement.

Noise interferes with external communication but also with internal auditory working memory. External communication interference can disrupt performance of tasks that involve teamwork. Working memory interference can disrupt information processing, especially holding available and manipulating units of information (e.g., reading and interpreting text, performing mental arithmetic, as well as remembering and understanding auditory information). Impacts on these fundamental cognitive functions likely make themselves felt "downstream" (i.e., later in the performance sequence) in more complex tasks, e.g., text comprehension, verbal communication, and long-term memory storage and retrieval.

Figure 4.1 provides an overview of the attributes of noise, the extent of research on its effects on performance, and its relevance for MAs.

4.2 Attributes and Units of Measurement

Noise can be defined as pressure variations in air resulting from vibrations that are perceived by humans to be annoying, unpleasant, and/or distracting (i.e., unwanted sound). The vibrations can originate from various sources, including equipment and vehicles; the movement of earth, water, or air; and from human or animal vocalizations. Being a special case of sound, noise shares sound's characteristics, including the following:

- Amplitude – the distance between the midline (or point of zero energy) of a wave and its crest or trough, which represents the amount of energy being transported by the wave (often characterized in units of root mean square [rms] over time when aperiodic). The larger the amplitude, the more energy the sound wave has, and the louder it will tend to be perceived.
- Frequency – the number of oscillations (cycles) in a simple sound wave that occur in one s. Frequency is measured in hertz (Hz) with 1 Hz being one cycle per second. Higher frequency sound will be higher in perceived pitch. Complex sound, effectively reflecting a spectrum of frequencies, is typically displayed as a frequency distribution by relative amplitude.
- Duration – the length of time the noise is present.

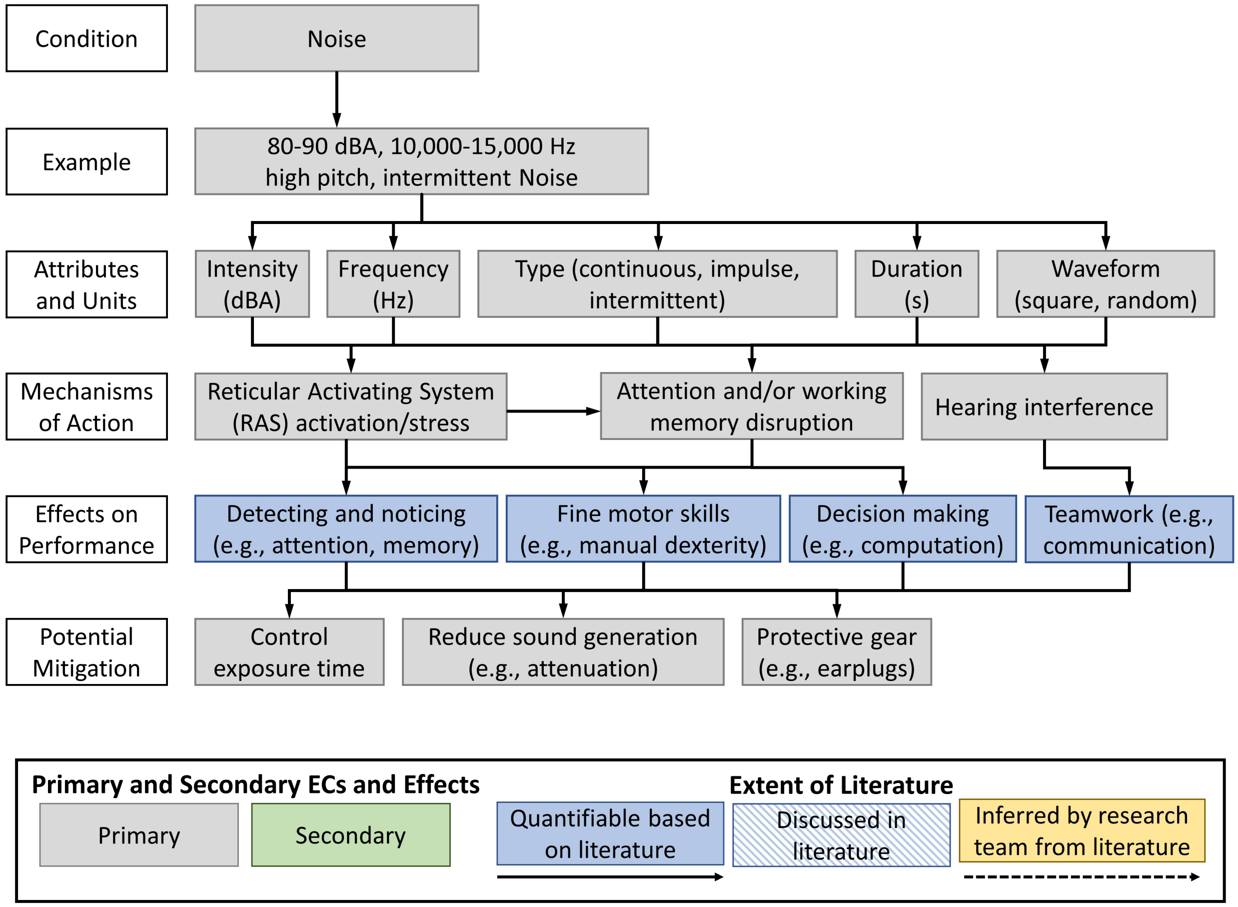

Figure 4.1 Noise effects overview[1]

- Waveform – the form or shape the noise wave takes. Waveforms can be described as the changes that occur in the noise's amplitude over time. Subtle differences in waveform can cause sounds of the same frequency and amplitude to be experienced differently (e.g., a concert high "C" played on a trumpet vs. saxophone).
- Periodicity – the sound waves of intermittent (aperiodic) noise are not equally spaced and have varying intensities, whereas continuous (periodic) noise waves are repetitious and equally spaced and have no variations or breaks in intensity.

The most common unit of measurement for the sound intensity level of noise is the decibel (dB), which is represented on a logarithmic scale of the ratio of a sound wave's amplitude relative to a reference amplitude. It can also be defined as the logarithm of the ratio of the stimulus' sound pressure (in Pascals) relative to a reference pressure[2]. Because the human ear is most sensitive to frequencies around 3,000 Hz and less sensitive to lower and higher frequencies, a weighted scale based on this frequency response, the A-weighted decibel (dB(A)), is often used when referring to the subjective loudness of noise. Figure 4.2 shows equal loudness curves for

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[1] Only some performance demands are listed here, as others may not be significant for the example condition.

[2] Reference pressure of 20×10^{-6} pascals, the pressure at which the average young adult can just detect a 1,000 Hz tone.

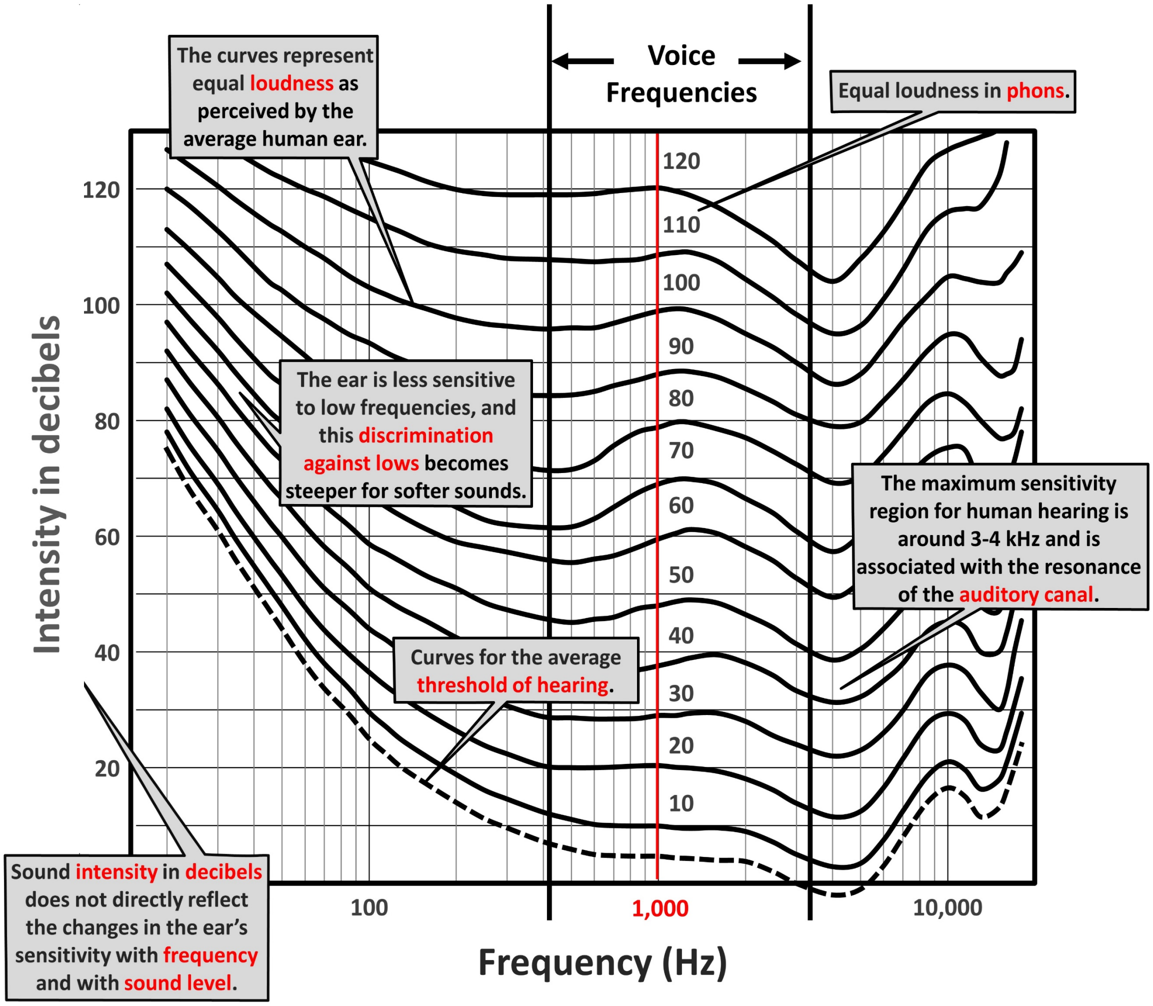

Figure 4.2 Equal loudness curves (after Nave, 2016). Subjective loudness measured in phons.

noises of different frequencies. As seen in the figure, the difference between noise intensity (in dB) and subjective loudness (measured in phons) varies for different frequencies. That difference is least in the 300–3,000 Hz frequency range, which is the frequency range of normal voice communication.

The sound levels experienced by workers in NPPs are likely to vary along the range shown in Figure 4.3. Noise levels in offices are likely to be approximately 65 dB(A), while noise levels in the turbine building of an NPP are very likely to exceed 85 dB(A) and may often be louder than 115 dB(A). Thunder from close lightning strikes is typically <120 dB(A) though if extremely close (<10 m) it will be experienced as a shock wave well above the threshold for pain (~140 dB(A), Rakov & Uman, 2003).

Various readily available electronic devices can be used to measure noise intensity (dB(A) and other characteristics) in industrial settings, including sound level meters, octave band analyzers, and noise dosimeters. Hand held sound level meters are often used to identify areas that

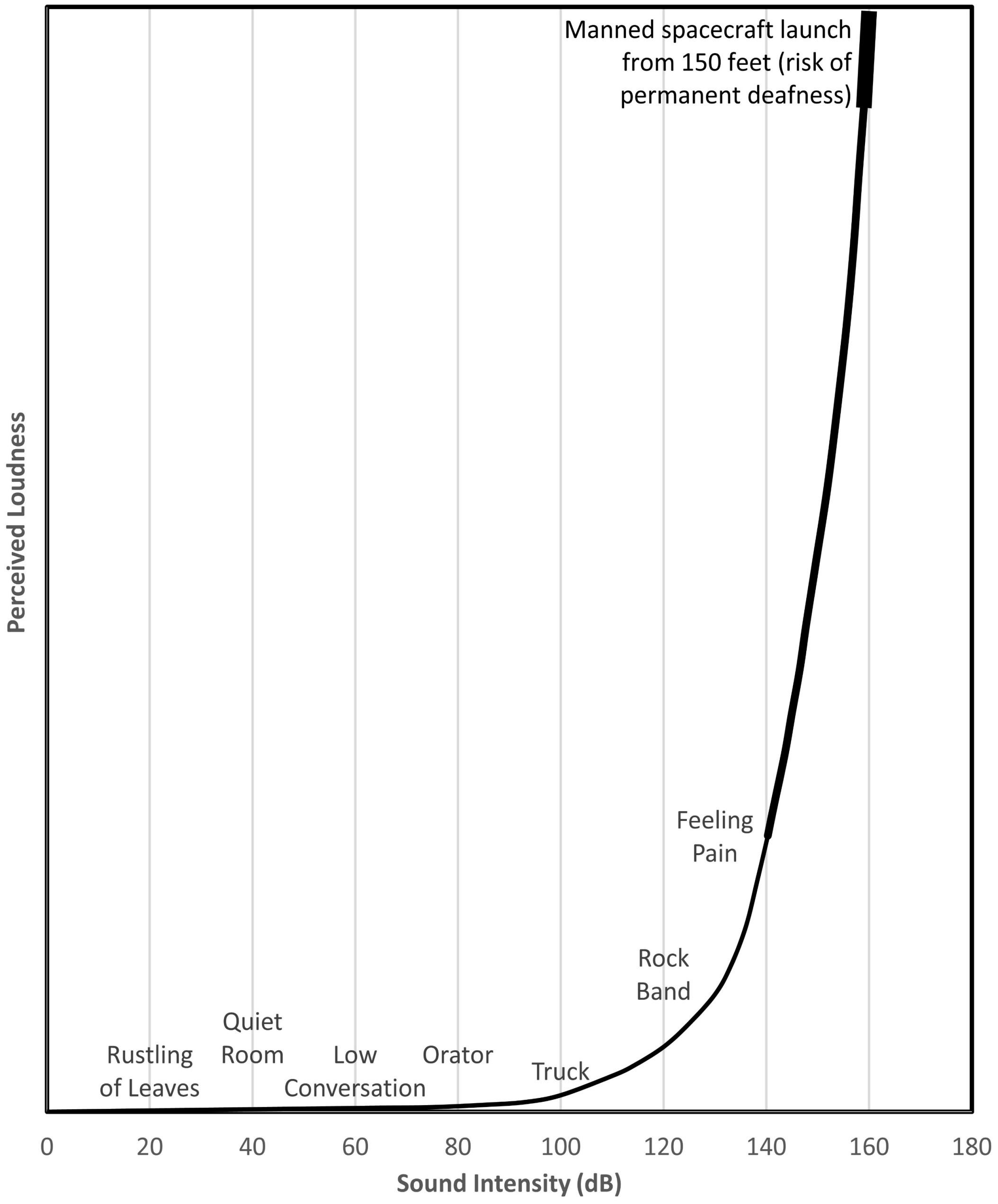

Figure 4.3 Relationship between perceived loudness and sound intensity (Source: NUREG/CR-5680, Echeverria et al., 1994 Figure 3-5)

feature elevated noise levels, and full shift noise dosimetry (see below) is used for further evaluation. An octave band analyzer allows evaluation of noise intensity at all frequency ranges relevant to human hearing. Taking readings at each of a number of frequency ranges provides a spectral signature of the noise, which allows an analyst to determine which octave bands contain most of the total radiated sound power. This information can be used to choose specific abatement approaches. Finally, a noise dosimeter is used to evaluate an individual employee's exposure during a sampling period. Noise dosimetry averages noise exposure over time and reports results as total work area exposure or a percentage of the permissible exposure limits (see Section 4.6 on Potential Mitigation Measures).

The figure, in addition to showing the loudness of some common sounds, shows how perceived loudness double for every 10 dB increase in intensity. At levels below 60 dB, the graph line is difficult to distinguish from the horizontal axis.

4.3 Time Variation of Noise

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to severe noise. More importantly, because the noise attributes during a flood may change, personnel exposure to this EC may also be variable in time. In other words, the severity of noise is time dependent and may vary significantly over the duration of execution of a manual action or task.

Figure 4.4 illustrates the variety of noises and variations in noise levels encountered during a hypothetical flooding event during which three MAs are performed sequentially (MA 1, MA 2, and MA 3). With the exception of operational machine and system noise, specific levels from the mix of sources may only be broadly estimable in advance. Consequently, statistical, probabilistic, and worst-case considerations are useful planning information for possible future flooding events.

4.4 Mechanisms of Action

Noise is primarily experienced through the hair cell receptors in the cochlea of the inner ear. These cells selectively resonate to the vibrations of the noise sound wave and this resonance is translated by the brain into perceived noise. In addition, low-frequency sound (2–200 Hz), which is emitted during storms and by road, industrial, and construction vehicles and industrial equipment (e.g., compressors, air conditioning units, generators, etc.), can be perceived through both hearing and touch (EnHealth Council, 2004). Low-frequency noise of this type can affect the semicircular canals of the inner ear, the body position, balance, and orientation sensors of the body. When this apparatus is impacted by intense (exceeding 130 dB(A)) low-frequency noise, even when the worker is not consciously aware of the stimulation, it can disrupt balance and induce a type of perceptual conflict illness (akin to seasickness that produces dizziness and nausea). These low-frequency noise impacts can substantially disrupt gross motor task performance (e.g., standing steadiness, walking carrying capability, as well as manual handling performances such as lifting, pushing, etc.). Low-frequency noise, perhaps not unexpectedly, tends to be rated subjectively as being more annoying than many other types of sound.

4.4.1 Stress, Arousal and Annoyance

Many of noise's effects on performance may be tied to its observed tendency to produce arousal, stress, and annoyance that affects an individual's ability to focus attention on the task at hand (Botteldooren et al., 2008; Schlittmeier et al., 2015). As noted above, noise can stimulate the reticular activating system of the brain, which is responsible for mediating the transition from baseline wakefulness to high attention, as well as the transition from sleep to wakefulness. The reticular activating system produces downstream effects in the hypothalamic-pituitary-adrenal axis to release stress hormones into the brain and bloodstream (e.g., cortisol, epinephrine, norepinephrine). The "fight-or-flight" response to stress and danger is produced by

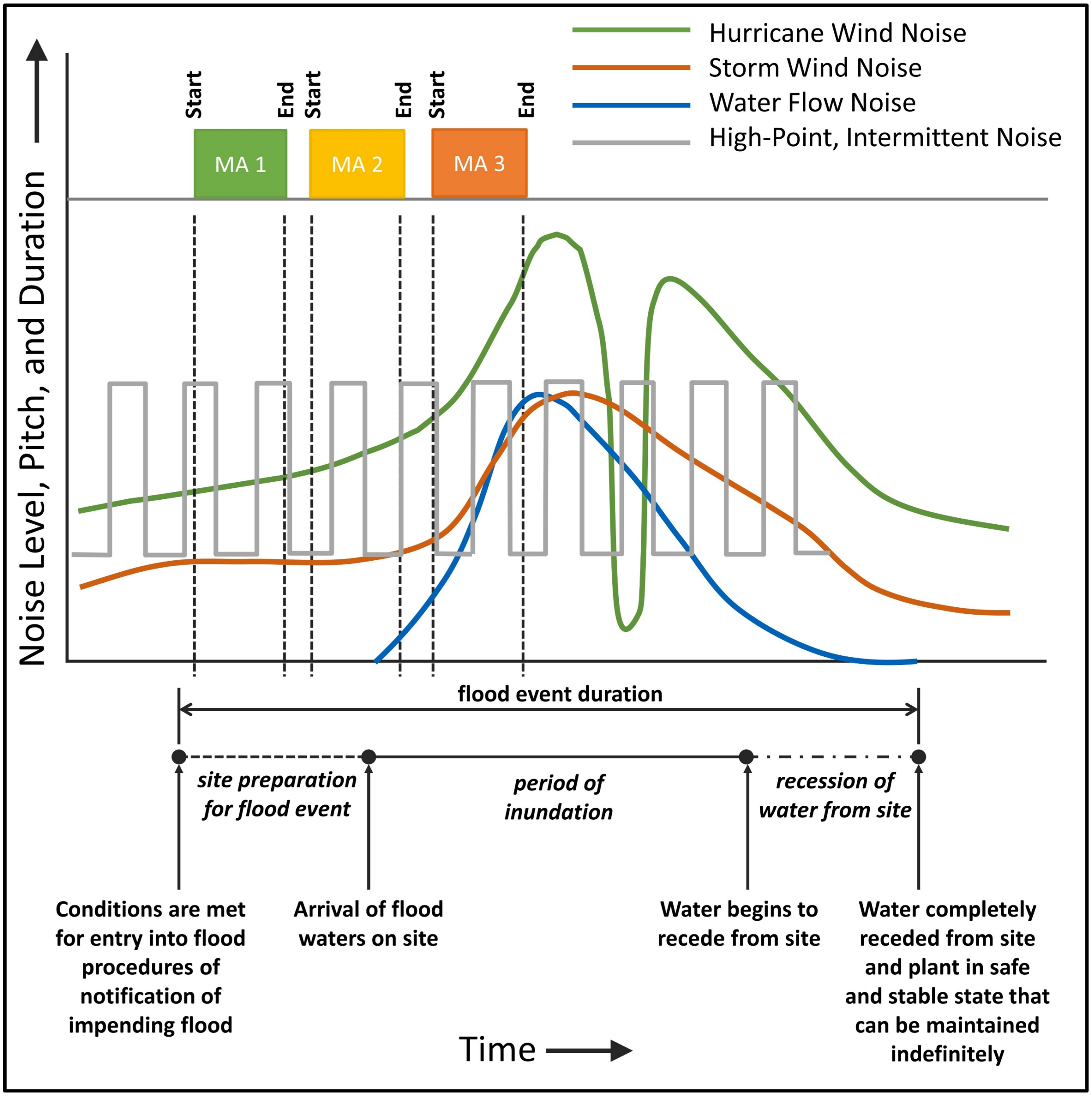

Figure 4.4 An illustration of noise variation during an example of a hypothetical flooding event

the reticular activating system (via epinephrine and/or norepinephrine). When noise is sufficient to produce reticular activating system activation, it could produce broad health and performance related impacts, from effects on transient cognitive performance (e.g., interrupting attentive and memory processes) to longer term stress related health effects on the body (e.g., ischemic heart disease, hypertension). While broadly enhancing gross flight-fight performance (e.g., strength), a high level of arousal in itself also interferes with performance involving complex skills, fine muscle movements, coordination, steadiness, and general concentration (Dovan, 2013). As with the direct effect of low-frequency noise noted above, reticular activating system activation may disrupt gross motor skills (e.g., standing steadiness, walking carrying, as well lifting, pushing, etc.). Supporting the practical import of the noise arousal theory is the fact that decreasing ambient noise in work environments has been shown to reduce job related stress (e.g., Leather et al., 2003), while exposure to continuous noise has been shown to lead to general depression or apathy in workers (arguably from extended flight-fight activation). These effects are more pronounced when noises start and stop out of the worker's control than when workers have some control over the noise (Broadbent, 1970; Klein & Seligman, 1976; Wohlwill et al., 1976).

4.4.2 Memory and Communication

Noise interferes with the phonological loop segment of working memory that deals with acoustic information, such as speech and the interpretation of written words. Consequently, noise disrupts the performance of tasks that involve processing verbal information: reading and interpreting text, as well as those involving remembering, understanding, and manipulating auditory information. In this regard, task irrelevant noise of diverse frequencies, intensities, and types can have particularly adverse impacts on articulatory working memory and disrupt attention to verbal information. This impact is either caused by interfering with the processes that maintain order within auditory working memory, or by interrupting the execution of deliberate rehearsal processes (Hughes et al., 2007). Impacts on these fundamental cognitive functions may also affect subsequent aspects of more complex tasks, such as text comprehension, verbal communication, and long-term memory (as well as further downstream effects indirectly on seemingly unrelated tasks, e.g., fine and/or gross motor task performance).

Speech noise, especially multi speaker background conversations, is among the most disruptive type of noise for many cognitive tasks, having effects that other nonlanguage types of noise do not (Sundstrom et al., 1994). Speech noise effects on performance are so ubiquitous they have been named "the irrelevant speech effect" (i.e., impaired recall in the presence of speech that is irrelevant to the task at hand) (Salamé & Baddeley, 1982). Particularly when the semantic content of the speech noise is relevant to the task at hand or the individual performing the task (e.g., the cocktail party effect described by Cherry, 1953), speech noise can access the phonological-loop working memory process, competing with and drawing attention away from ongoing verbal and/or reading tasks. These tasks require the individual to maintain and operate on information in current focal attention, and the informational content in irrelevant speech noise can replace workers' task relevant verbal information in the phonological loop. This replacement degrades the memory trace and affects performance of downstream tasks, such as long-term memory and communication tasks. Figure 4.5 presents Baddeley's (Baddeley & Hitch, 1974) model of how speech noise affects the working memory process for verbal tasks by competing for limited resources in the phonological loop.

Research has shown that there is considerable individual difference in how severely both non-speech and speech noise affects cognitive functions. Individuals with particularly high working memory capacities appear to be less susceptible to auditory distraction by task irrelevant speech noise than individuals with lower capacities (Sörqvist, 2010). Individuals with high working memory capacities also appear to be able to overrule the distractive nature of task irrelevant speech through cognitive control.

4.5 Effects on Performance

4.5.1 Overview

Noise can cause a variety of direct and indirect effects on both health and task performance. Sudden and/or prolonged loud noise, as noted earlier, can do direct damage to the noise

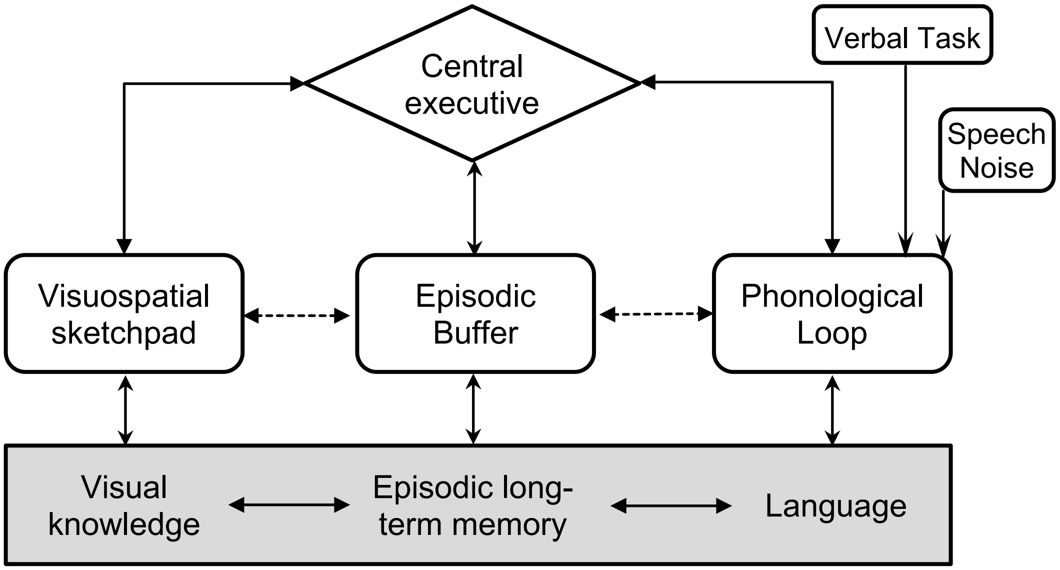

Figure 4.5 Baddeley's working memory model (Baddeley & Hitch, 1974)

detecting hair cells, often causing permanent hearing loss along specific frequency regions. Short-term exposure to loud noises can produce temporary changes in auditory perception, making ears feel stuffed up and sounds appear temporarily quieter, a symptom of a temporary threshold shift. It may also cause temporary tinnitus or ringing in the ears. These effects may last for minutes to hours after noise exposure, but, if repeated, can lead to permanent hearing loss and/or tinnitus. The distraction and annoyance of noise can affect aural communication, attention, simple and complex cognition, vigilance, and fine motor skills.

4.5.2 Aural Communication

Noise can affect aural communication, primarily by masking the communicated information (i.e., affecting the receiving pathway). Masking can be especially problematic during busy responses to floods and other incidents at NPPs when machinery, vehicles, and workers are all moving through a location simultaneously and/or there is ongoing storm related noise. The noise masking effect on communication may have a significant causal relationship with noise related incidents and accidents. High noise levels have been associated with higher accident and error rates, as well as lower productivity (Broadbent & Little, 1960; Noweir, 1984; Wilkins & Acton, 1982); whereas, reducing workplace noise levels has been found to reduce both error and accident rates (Broadbent & Little, 1960; A. Cohen, 1974). The need to maintain receiving pathways for sound creates a tradeoff dilemma regarding the use of noise blocking equipment (e.g., ear plugs) for those working in noisy environments.

4.5.3 Attention

Noise conditions that individuals find most annoying have the greatest detrimental effect on the performance of tasks that require attention (Schlittmeier et al., 2015). Studies of environmental noise in communities have found that above ~50 dB(A), every 5 dB(A) increase in sound intensity increases the percentage of the population that finds it annoying by about 10 percent (Schultz et al., 1976; USEPA, 1973). In Figure 4.6, sound levels are plotted against the percentage of workers who are highly annoyed, as determined through extensive surveys.

Above 70–80 dB(A), most workers will be highly annoyed. This is near the industry recommended health standard of 85 dB(A) for an 8-h day (see Section 5.8). Thus, adverse performance effects are expected even at these acceptable noise levels. Subjective annoyance reactions to noise may have a reciprocal relationship with noise's perceptual and cognitive effects. Annoyance may be driven by subjects' perceptions of effects on their ability to maintain attention and other perceptual and/or cognitive faculties, or noise related annoyance may be a partial cause of these performance effects.

4.5.4 Simple and Complex Cognition

The effects of noise on simple and complex cognitive task performance have been studied extensively in office and industrial environments as well as in research laboratories. Continuous noise typically has little if any effect on simple perceptual tasks not involving audition (e.g., through interference. Noise has clear detrimental impacts on psychomotor integration tasks (e.g., driving and other tasks where two limbs are involved in control), cognitive tasks involving attention and memory, and more complex tasks involving verbal information (e.g., verbal communication and verbal and reading comprehension) (Hancock & Desmond, 2001). Noise also tends to show a greater negative influence on task performance accuracy than completion speed. Intermittent (or aperiodic) noise tends to disrupt performance of these tasks more than continuous noise (Casali & Robinson, 1999; Szalma & Hancock, 2011).

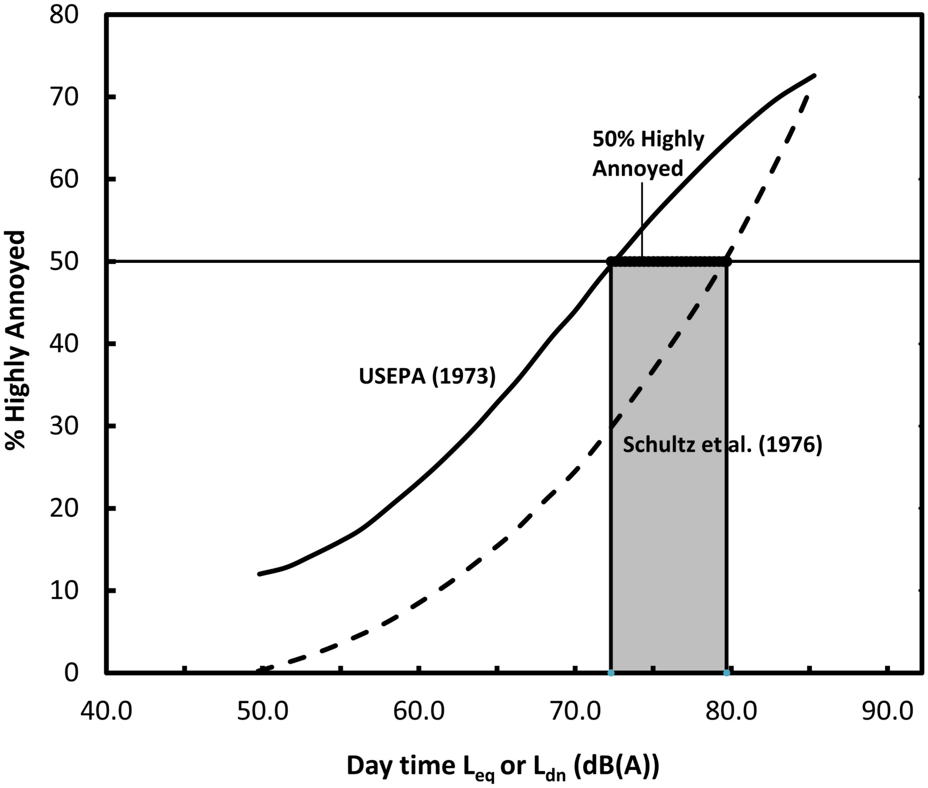

Figure 4.6 Percentage of respondents highly annoyed by outdoor noise level. Curves fitted to results from several social surveys in different countries.

The Salamé-Baddeley (1982) irrelevant speech effect is one of the most consistent effects of noise on cognitive performance. As indicated in earlier sections, speech noise that is irrelevant to the task at hand shows distinct effects on a number of cognitive tasks that are fairly independent of noise intensity, at least at normal ~55–95 dB(A) speech intensity ranges (Jones, 1990) Irrelevant speech, as discussed earlier, appears primarily to affect processes involving working memory (e.g., reasoning, mental arithmetic, and problem solving) rather than attention. Further, meaningful speech disrupts reading and text comprehension more than meaningless (unrelated words) speech (Jones, 1990). Clearly, particularly significant irrelevant speech noise impacts are to be expected on verbal tasks rendered in office environments, where meaningful side conversations are common.

Both generalized and speech related noise show their clearest disruptive effects on auditory perception and higher-level cognitive processing involving the auditory modality. However, a body of recent evidence suggests these disruptive effects may cross modalities as well. Reflecting this, Hidaka and Ide (2015) presented bursts of white noise with a visual stimulus (Gabor orientation patches) where participants were instructed to make an orientation decision (left or right tilt of lines). The authors found that noise presented both at the same time as the target visual stimulus (temporally congruent), and same side as the target stimulus (spatially congruent) maximized mistaken decisions. The authors suggest that suppression of the visual task by temporally and spatially congruent auditory noise may reflect an adaptive process. This process serves to reduce a weaker visual input to optimize processing of the stronger and/or more salient auditory input (even though not central to the visual task in focus). The Hidaka-Ide results may also be interpreted as reflecting the difference in processing speeds for auditory and visual stimuli, auditory signals being processed ~30 milliseconds before simultaneously presented visual signals (Bittner, 1972). It should be noted that this is one of only a small number of studies demonstrating a cross modal effect and thus it may be very specific to the particular combination of noise characteristics and cognitive tasks examined. A meta-analysis showing no effect of auditory noise on visual tasks reinforces this possibility (Szalma & Hancock, 2011). Further research is needed to clarify whether noise affects naturalistic visual tasks under conditions pertinent to NPPs.

4.5.5 Vigilance

Vigilance tasks, especially those requiring routinized manual responses to relatively frequent targets, show fairly consistent effects of noise (Kjellberg, 1990). These effects often involve increased fast response errors, which may reflect an inability to withhold routinized motor responses in the presence of noise stress. In other vigilance studies, subjects have shown specific accuracy reductions for low-probability targets as well as an inability to adapt effectively to changes in target probability (Dornic & Fernaeus, 1981; Smith, 1985). This latter effect probably reflects a strategic shift by subjects to focus noise limited attention on certain stimuli (e.g., high probability stimuli) at the expense of others. Vigilance and other focused attention tasks appear especially vulnerable to ongoing noise that is unpredictable in period, frequency, and intensity (e.g., Smith, 1988; Smith & Miles, 1987).

4.5.6 Fine Motor Skills

Evidence of noise effects on performance of fine motor tasks is somewhat equivocal. Sudden, loud noise reliably produces startle effects, disrupting nearly all fine motor tasks at least temporarily (e.g., May & Rice, 1971). More recently, Nassiri et al. (2013) detected negative effects of noise on several practical fine motor control and manual dexterity tasks. In this study, the authors varied the periodicity, intensity, and frequency of the noise, concluding that aperiodic and high-frequency noise were especially important in determining these effects. However, an earlier study by Weinstein and MacKenzie (1966) found that white noise at 100 dB actually improved manual dexterity, supporting the inverted-U hypothesis[3]. It is likely that the true pattern of noise effects on fine motor tasks, beyond those evoking startle responses, is highly dependent on the specific noise characteristics such as intensity, frequency, and periodicity, albeit accident and productivity data indicate that it is probably safe to assume detrimental effects in noisy industrial settings.

4.5.7 Noise Effects on Taxons

Hancock et al. (2005) proposed estimates of the impact of noise on each of several taxons (i.e., variants of the performance demands discussed in Volume I). In this approach, the impact of noise is represented as an impact factor, reflecting the percentage degradation or improvement that noise causes to baseline levels of accuracy and speed. As can be seen in Table 4.1, the authors maintain that the impact of noise on the speed and accuracy of perception are minimal, but they do not discriminate verbal/textual auditory and visual perception tasks from those of other modalities. As discussed by Jones (1990), Hancock et al. suggest significant noise adversely impacts both speed and accuracy of numerical analysis. They maintain that noise has a significant impact on the speed of discrete fine motor skills and a moderate impact on both the speed and accuracy of continuous fine motor skills. Also, similar to other authors, they assert that noise affects the accuracy but not the speed of reading/writing and oral communication (Szalma & Hancock, 2011). These estimates may be useful in providing a sense of the breadth of adverse impacts of noise on NPP worker performance but should probably not be taken as hard rules.

4.5.8 Recommended Limits

The major health and safety organizations have published permissible exposure limits for sound intensity exposures. When noise levels and durations exceed the standards, worker exposure should be controlled. As seen in Table 4.2 the NIOSH and ACGIH standards recommend a

Table 4.1 Proposed taxon impacts of noise for the IMPRINT Model

IMPRINT Taxon	Accuracy	Speed
Perception – Visual Recognition/Discrimination	-0.4%[(a)]	2.4[(a)]
Numerical Analysis	-31.8%	-16.8%
Fine Motor Discrete	-9.9%[(a)]	-33.6%
Fine Motor Continuous	-19.9%[(a)]	-13.1%[(a)]
Communication – Reading & Writing	-23.7%	1.4%[(a)]
Communication – Oral	-29.0%[(a)]	ID[(b)]
Positive percentages reflect facilitation of the task, negative percentages reflect decrements. (a) The confidence intervals for these effects contain zero, thus noise may have very small or zero statistical effect on these tasks. (b) Indeterminate		

Source: based on Hancock et al., 2005

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[3] The “inverted-U hypothesis posits that an operator’s performance tends to graphically follow an inverted-U course as stress/activation is increased. Typically, there is a low level of performance at a low stress/activation level. This, with stress/activation increases, is then followed by an increase to something of a (maximal) performance plateau before ultimately a downward slide in performance (Lysaght et al., 1989).

Table 4.2 Limits for noise over an 8-hour period by various regulating agencies

Agency	Permissible Exposure Limits
OSHA	90 dB(A) (TWA)[a]
NIOSH	85 dB(A) (TWA)[b]
ACGIH	85 dB(A) (TWA)[c]

(a) 29 CFR 1910 (1996) *OSHA General Industry Regulations, Subpart G Occupational Health & Environmental Control, §1910.95 Occupational noise exposure*
(b) Rosenstock (1998)*. Criteria for a recommended standard: Occupational noise exposure. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention.*
(c) American Conference of Governmental and Industrial Hygienists (2006)*.*

maximum 8-h day exposure limit of 85 dB(A), whereas OSHA recommends a maximum of 90 dB(A)/8-h day. Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure.

4.6 Potential Mitigation Measures and Their Effectiveness

A variety of mitigation measures are available to reduce worker exposure to noise (e.g., Weinstein, 1982). Research has shown that adverse performance effects occur at noise exposures below those considered safe limits and that noise abatement measures are effective in raising productivity and reducing accidents (Broadbent & Little, 1960). Mitigation strategies involve noise abatement and/or protecting the worker, as discussed below. Noise abatement strategies could include the following:

- Isolate or dampen machinery that produces noise through its vibrations. This can be accomplished passively using flexible materials and mechanical linkages to absorb the vibrations, or actively using sensors or actuators to produce destructive interference that serves to cancel out the noise.
- Modify the speed of the machinery to lower the intensity of vibrations or to produce different, less annoying vibration frequencies.
- Reduce or eliminate sound transmission to the workforce, if the equipment cannot be silenced or significantly dampened.
    - Reduce high-frequency noise exposure by increasing the distance between the noise source and the worker. Increasing distance is less effective for equipment that produces highly annoying low frequencies, which attenuate less rapidly over distance than high frequencies (EnHealth Council, 2004).
    - Place barriers of sound reducing material between the noise source and the worker; isolate the work area from the noise using sound proofing materials. These materials can absorb 70 percent of the noise that strikes them and are effective for both low- and high-frequency noise.
    - Reduce irrelevant speech noise, especially during the performance of essential tasks.

Worker protection strategies could include the following:

- Provide effective ear protection and enforce its use. Workers should use ear protection when exposure is above that identified in Table 4.3 and it cannot be abated by other methods. Because ear protection can mask both noise and important sounds, thereby impairing communication and leaving the user open to accidents and/or injury, noise abatement is a first priority.

  - Recent scientific advances have produced active hearing protectors, which contain electronics that cancel incoming sound waves. These protectors have potential, but a recent review (Giguère et al., 2011) suggests they may under or overprotect at different times, and that they should be tested against standards to assure they do not allow more than 85 dB(A) through to the ear under a wide range of ambient noise circumstances.

- Limit the time workers spend in noisy environments, especially when allowable noise is continuous, or workers are exposed to aperiodic noise or low-frequency noise.

4.7 Interactions of Noise with Other Environmental Conditions

During weather events, noise may co-occur with heat, cold, wind, lightning, and standing and moving water. Vibration is also likely to accompany noise.

4.8 Summary of Research on Noise Impacts

The state of the research literature regarding the impacts of noise on performance demands is summarized in Table 4.4.

Table 4.3 Allowable noise level from OSHA and NIOSH/ACGIH standards

OSHA Level dB(A)	Allowable Duration	NIOSH/ ACGIH Level dB(A)
90	8 h	*85*
95	4 h	88
100	2 h	91
105	1 h	94
110	30 min	97
115	15 min	100

Sources: OSHA: 29 CFR 1910.95, 1996; ACGIH, 2006

Table 4.4 Noise effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(a) (d) (e) (f)
Sensation and visual recognition	2	(a) (d) (f)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	4	(a) (d)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, & evaluating/selecting options	1,3,4	(a) (b) (d)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	1,3	(a) (c) (d)
Gross motor skills – heavy and light	4	(a) (d)
Other neurophysiological functions	4	(a) (d)
Teamwork		
Reading and writing	1	(a) (b) (d) (e) (f)
Oral face-to-face and electronic communication	2	(a) (d) (e)
Cooperation, crew interaction, and command and control	2,4	(a) (d) (e)

Assumptions and Limitations of Applicability

(a) The type of noise can have radically different effects, depending on the particular mix of performance demands making up a task. Therefore, research effects tend to be on very controlled tasks and noise types, which makes generalization difficult.

(b) The Hancock et al. (2005) IMPRINT model recommendations claimed statistically significant impacts on accuracy and speed, and provided a magnitude of the impact of noise on numerical analysis, fine motor-discrete, and reading and writing skills, but did not recommend specific impacts by type and/or magnitude of noise (see Table 4.1), which are important factors when determining the effects on performance demands. These estimates might be useful for bracketing possibly expected negative impacts of noise on NPP worker performance, but they should not be taken as hard rules.

(c) Hancock et al. (2005) claimed a consistent effect on fine motor, but other authors have also shown either no effect or improved performance under certain contexts.

(d) Sudden, loud noise evokes startle effects and can disrupt most tasks completely for a short period of time.

(e) Speech noise has very consistent effects on communication, comprehension, production and working memory.

(f) Noise can completely disrupt auditory perception and may cross modalities to visual perception.

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) No information (a gap).

5 VIBRATION

5.1 Introduction

Vibration can be defined as an oscillating motion that serves to transfer mechanical energy. It is characterized by a >1 Hz frequency, or frequency spectrum, and associated acceleration.[1] Transmitted from objects and dissipated in the body, the mechanical energy of vibration may induce a variety of human performance effects. Vibration of the body can be divided into (1) whole-body vibration, and (2) single, exposed limb vibration. Of these, whole-body vibration is produced when vibration is transferred from vibrating support structures into the whole of the body (e.g., via the seating in a moving vehicle, floors in contact with heavy machinery).

Particularly with regard to gross motor activities, most behavioral effects research addresses whole-body vibration. Whole-body vibration has consistently shown adverse effects on visual acuity and manual tracking tasks, such as those involving eye-hand coordination and fine motor skills, as well as on postural stability with effects on standing steadiness and associated gross motor activities (e.g., walking). Costa et al. (2014) have reported substantial evidence of cognitive effects with occupationally relevant exposures; however, such effects have historically appeared more equivocal (see Griffin, 2012). Significant effects also appear to be associated with longer exposure, with “perceptual conflicts” arguably arising from vibration induced optical blur and vestibular (e.g., Bittner & Guignard, 1985a, 1985b; Helmkamp et al., 1984). These are reflected in post whole-body vibration standing-unsteadiness effects and sometimes nausea with some cognitive indications. Research indicates that cognitive task performance may be enhanced at low levels of whole-body vibration but then degrades rapidly as discomfort increases. In part, this is attributed to mechanical interference with responding (Woldstad et al., 1982), which broadly appears to be a reflection of the inverted-U relationship between significant stressors (and stress hormones) and cognitive performance (e.g., Lupien et al., 2007). The complexities of these relationships are not yet fully understood and remain an area for future research.

Exposed limb vibration tends to occur most often when personnel use an oscillating tool or operate a control that is located or linked to a vibrating surface. In both cases, the primary effect is transmission of vibration into the limb in contact with the device (e.g., hand-arm vibration-), which affects the accuracy with which the individual can control the device. Long-term or chronically exposed limb vibration also may cause permanent vascular, neural, and musculoskeletal disorders in the limbs (Popević et al., 2014)[2]. The majority of the research literature on vibration considers only behavioral effects while the vibration is occurring. However, as shown by Popević et al. (2014), chronic exposure effects may continue after the stimulus ceases (e.g., Griffin, 2012; Helmkamp et al., 1984; Savage et al., 2016). In actual work environments, vibration very often coincides with other ECs. For example, vibration rarely occurs in the absence of noise (e.g., mechanically induced vibration in air), but may also co-occur with heat, cold, and moving water during flooding events. Figure 5.1 summarizes vibration attributes, literature support levels, and MA relevance.

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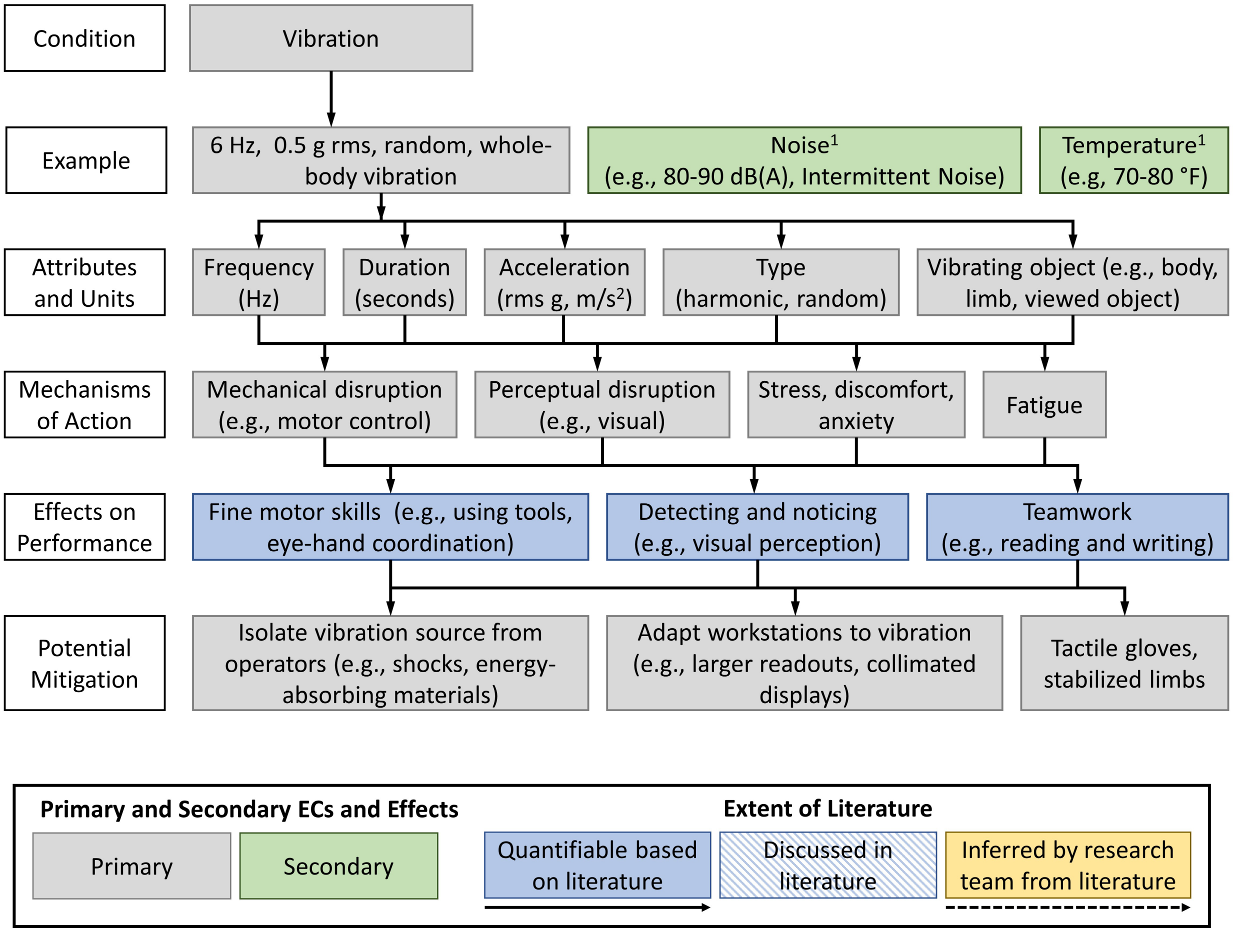
[1] Very low frequency (<1 Hz) oscillatory motion is not a large concern in the present research context because it is most typically an issue for extended transits aboard ships, aircraft, and other conveyances (Bittner & Guignard, 1985a, 1985b; Griffin, 2012; Kennedy et al., 2004).

[2] Cold is noted as chronically interacting with vibration in the development of Hand-Arm Vibration Syndrome.



[1] See noise, cold, and heat EC figures

Figure 5.1 Vibration effects overview[3]

5.2 Attributes and Units of Measurement

The oscillation inherent in vibration is characterized primarily in terms of frequency and acceleration. Of these, frequency is often measured in terms of the number of oscillation cycles per s, which are expressed in scientific units of hertz (Hz), with 1 Hz = 1 cycle per s. Acceleration is proportional to the force (also referred to as severity) of the vibration and is often measured in meters per second-squared (m/s^2). Acceleration may also be expressed in terms of the acceleration due to gravity (g), which is 9.8 m/s^2 (hence, an acceleration of 1 g = 9.8 m/s^2). Because acceleration and the frequency spectrum tend to change over time, instruments that measure vibration acceleration often display the peak acceleration, its root mean square (rms), or its average absolute value rather than attempting to characterize the entire wave structure over time. These averaged acceleration values may be expressed in units of rms (m/s^2), rms (g), or peak-g.

The waveform, or shape of the vibration wave, is a third characteristic of vibration whose differential effects on performance have not been studied in detail. The waveform is the pattern

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[3] Only some performance demands are listed here, as others may not be significant for the example condition.

of peaks and troughs in the vibration. Echeverria et al. (1994) noted that vibration can be characterized into three broad categories:

- simple harmonic vibration – is a simple repeating motion.
- complex harmonic vibration – is a more complicated repeating motion consisting of a combination of simple harmonic vibrations with different frequencies and accelerations. Instead of having a single peak in each cycle, complex harmonic vibration might have several peaks of differing amplitude in each cycle.
- random vibration – consists of a series of motions that occur without a systematic pattern. Most vibration tends to be random.

The direction of the vibration can also be characterized with respect to the direction(s) of propagation in three-dimensional space in relation to a vibrating object or the worker. From the perspective of a seated individual, a vibration's motion can occur in any combination of front-to-back (x-axis), side-to-side (y-axis), and up-and-down (z-axis). Small accelerometers may be orthogonally mounted to measure vibration in these three directions. These devices can be mounted on a vibrating object to measure its vibration or placed on the surface supporting the worker to measure whole-body vibration (NUREG/CR-5680, Echeverria et al., 1994).

Exposure time (in s, min) is a fifth important characteristic of vibration when it applies to the human body. This may be measured by the specific accelerometer apparatus used or a simple timing device.

5.3 Time Variation of Vibration

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to severe vibration. More importantly, because the vibration attributes during a flood may change, personnel exposures to this EC may also be variable in time. In other words, the severity of vibration is time dependent and may vary significantly over the duration of execution of a manual action or task.

Figure 5.2 demonstrates random waveform, variable frequency, and intensity vibrations as they might occur during a flooding event. As shown, three MAs (MA 1, MA 2, and MA 3) may be subjected to somewhat different mixes of these vibrations. Components of these mixed vibrations may be anticipated during use of hand tools, moving vehicles, as well as from some stationary equipment (e.g., powered torque wrench, vehicles, and generators). However, storm induced vibrations, in contrast to this equipment related sources, may be difficult to anticipate and characterize immediately before or during a flooding event. Statistical, probabilistic, and worst-case scenario analyses may be used for consideration of storm induced vibrations.

5.4 Mechanisms of Action

Researchers studying the effects of whole-body vibration on performance have long identified mechanical disruption of perception, stress and anxiety, discomfort, and fatigue effects from exposure to vibration, but few have addressed both vibration's mechanisms of action and the potential for modulating them (Lupien et al., 2007; Woldstad et al., 1982). Recent meta-analyses of vibration effects on human performance (e.g., Conway et al., 2007; Hancock et al., 2005) suggest that despite the perception among some researchers that vibration's effects on performance have been settled, the mechanisms by which vibration causes some of its effects

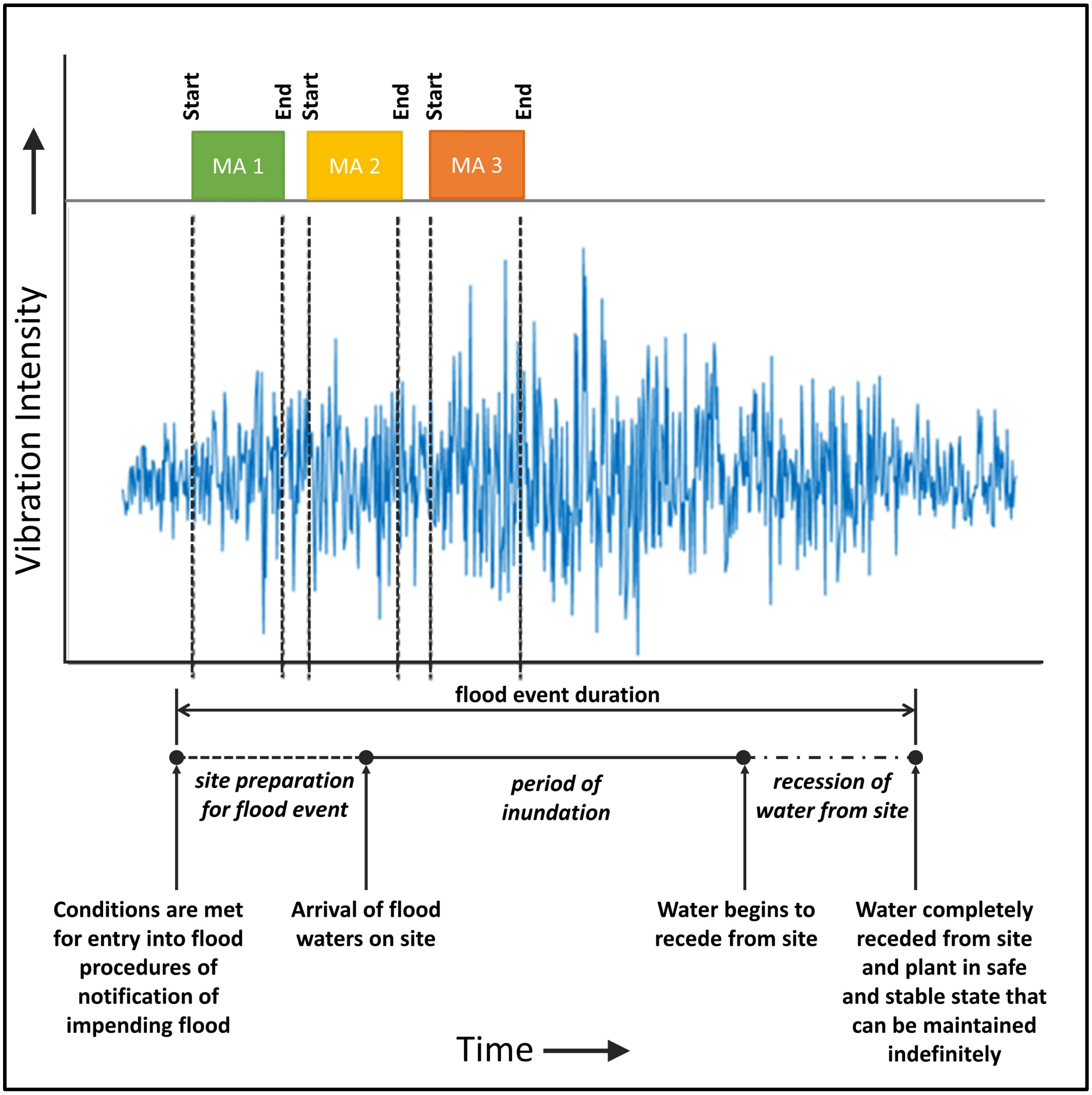

Figure 5.2 An illustration of vibration variation during an example of a hypothetical flooding event

and their interactions are not thoroughly understood. Reflecting this, the Conway et al. (2007) meta-analytic study suggests that research on vibration has had quality issues, because only 13 of 224 relevant papers on whole-body vibration met their inclusion criteria.[4] Not surprising, in their study, they reported that the most consistent and largest effects of whole-body vibration on performance were on performance of perceptual tasks.[5] Both whole-body and object vibration,

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[4] Exclusion criteria were based on the judged quality of studies by the authors using a mix of criteria, including data being sufficient for computing effect sizes (often missing in older studies).

[5] Hedge's g = -1.79, which indicates a large effect size.

as noted earlier, can blur vision or the appearance of an object or readout, thereby interfering with visual acuity (particularly for vibration approaching 30 Hz). This affects reading accuracy and any subsequently associated cognitive or motor activities.

5.4.1 Disruption of Perception

The mechanism by which vibration affects visual and manual tracking tasks is straightforward. First, moving stimuli are less easy to apprehend visually and relative movement between the viewed object and the retina results in image blurring. Poorer visual performance is a consequence. Some methods may be used to minimize this induced blur (e.g., collimated display[6]) and reduce the associated performance decrement. When the eye itself is vibrating at or near its resonant frequency of 30 Hz, vision can be completely disrupted (Lawton & Miller, 2006).

5.4.2 Mechanical Disruption of Motor Control

Vibration mechanically disrupts the control needed in tracking tasks or tasks requiring fine hand and/or arm control. Methods of stabilizing the hand and arm can markedly enhance performance, as illustrated by Woldstad et al. (1982). Both visual perception and more complex tasks that require input via visual perception and/or controlled motor responses are likely to show vibration effects when the frequency and/or acceleration become sufficiently severe.

5.4.3 Stress, Arousal, and Discomfort

Vibration effects on performance may also be mediated through stress and anxiety, which have well demonstrated effects on arousal. Some studies (e.g., Ljungberg et al., 2004; Jessica K. Ljungberg & Neely, 2007) have shown increased subjective stress and aversiveness with vibration, especially when exposure durations were increased for individuals particularly sensitive to vibration. Subjective discomfort studies have noted errors, in part attributed to the tendency of exposed individuals to rush to complete a task and/or become preoccupied with the discomfort. Discomfort appears to be a function of both the vibration frequency and acceleration, as well as the duration of exposure. Many studies involving vibration, particularly the earliest, examined only relatively short exposure times (Conway et al., 2007). Studies of longer exposures found both greater subjective discomfort and more chronic effects (Helmkamp et al., 1984; Ljungberg, 2009). This is not surprising given the well-established generalized effects of stress, anxiety, and discomfort on arousal and performance (see Hancock & Desmond, 2001; Lupien et al., 2007).

The ISO historically has provided guidance on the combined frequency acceleration ranges that individuals can tolerate before experiencing discomfort as seen in Figure 5.3. In the figure, exposure boundaries are shown across frequencies with points above an exposure time curve being tolerated for a shorter time than points on or below the curve. Discomfort would likely be a primary concern (if any were an issue). The rms-g discomfort limits for even relatively short periods (e.g., <0.04 rms-g across the frequency spectrum at 1 hour) are well below any expected effects for visual acuity (>0.1 rms-g at all frequency levels as seen in Figure 5.3) and essentially below those for initial effects on manual tracking (itself only an ~10 percent tracking variation at >0.1 rms-g).

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[6] A display that uses mirrors or other technology to produce a parallel (or close to parallel) beam of rays; a display that provides a long viewing distance for the observer

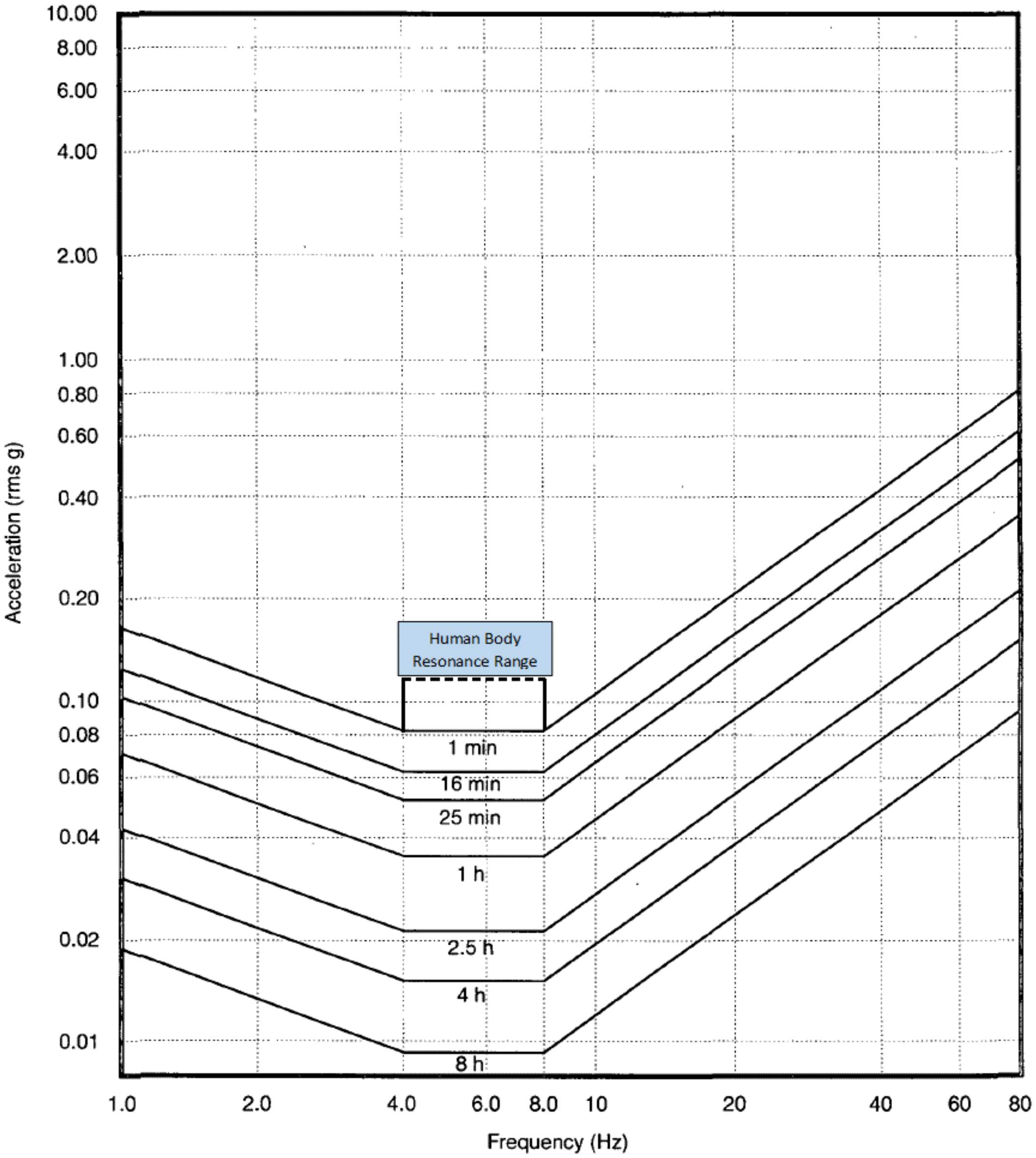

Figure 5.3 Discomfort boundaries by exposure time and observed vibration characteristics (ISO in NUREG/CR-5680, Echeverria et al., 1994)

5.5 Effects on Performance

Workers exposed to whole-body vibration experience effects on attention, visual acuity, and manual tracking.

5.5.1 Attention

Vibration effects on attention related performance, likely mediated through stress and anxiety, tend to follow the discomfort tolerance limits shown in Figure 5.4. Studies of discomfort effects have found that individuals tend to make more errors as they rush to complete tasks and/or become preoccupied with discomfort (e.g., Griffin, 2012; Guignard et al., 1982; Ljungberg et al., 2004). Guignard et al. (1982) reported that attention sensitive performances tended to follow the discomfort lines established by the ISO as shown in Figure 5.4, but that visual performance did not (as reflected in Figure 5.3 vs Figure 5.4). Reza et al (2012) showed that vibration increases both subjective and physiological workload (i.e., National Aeronautics and Space Administration [NASA] Task Load Index and heart rate), adversely affecting reaction time performance. Studies by Seidel et al. (1988) and Ljungberg and Neely (2007) indicated that both strain and cognitive aftereffects follow vibration exposures. These patterns of vibration effects on attention and related cognition are consistent with the generalized effects of stress, anxiety, and discomfort on arousal and performance (see Hancock & Desmond, 2001; Lupien et al., 2007).

5.5.2 Visual Acuity

The ability to read text and distinguish objects visually is dependent on frequency and acceleration, as seen in Figure 5.3. The broken curve in Figure 5.4 represents the combinations of vibration frequency and acceleration under which error-free reading may be anticipated. For each subsequent curve above 0 percent, the probability that a single character will be misread increases by 10 percent. When the characters are part of text, however, the effects of vibration may be overcome by the context that meaningful phrases or sentences provide (e.g., Tulving et al., 1964). The adverse effects may also be moderated for numerical sequences where second readings can serve as a check against important misreads.

5.5.3 Cognition

A meta-analysis conducted by Conway et al. (2007), based on only 13 articles, included only one providing evidence that cognitive processes were moderately susceptible to whole-body vibration[7]. In contrast, Sherwood and Griffin (1992) had previously shown differences in learning rates for visual stimuli for a subject population undergoing vibration; and later for learning name team associations. Likewise, Schipani et al. (1998) showed decrements in time sharing, memorization, inductive reasoning, attention, and spatial orientation after vibration. However suggestive, neither of these latter studies was designed to disentangle the vibration’s higher cognition effects from simple input/output visual perception and motor effects. For example, Ljungberg and Neely (2007) found that when noise was present with whole-body vibration, perceived stress was significantly higher than with noise alone, suggesting a cognitive interaction of noise and whole-body vibration. This theoretical disaggregation of effects is unlikely to be of operational concern because noise and vibration are expected to be coupled in flooding events where vibration is an issue.

Sustained >1 Hz vibration can lead to nausea or motion sickness (Helmkamp et al., 1984), which have been found to negatively affect subjects’ abilities to perform a variety of perceptual and cognitive tasks after vibration exposures (Lawton & Miller, 2006). Relatively brief rest periods following exposure can remedy motion sickness in most people. Simple harmonic vibration was judged most likely to impair performance by causing nausea or motion sickness (NUREG/CR-5680, Echeverria et al., 1994). Low-frequency (<1.0 Hz) vibration over time also. tends to induce motion sickness (Bittner & Guignard, 1985a, 1985b; Griffin, 2012; Hancock et al., 2005).

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[7] Hedge’s g = -0.52, indicating a moderate effect size.

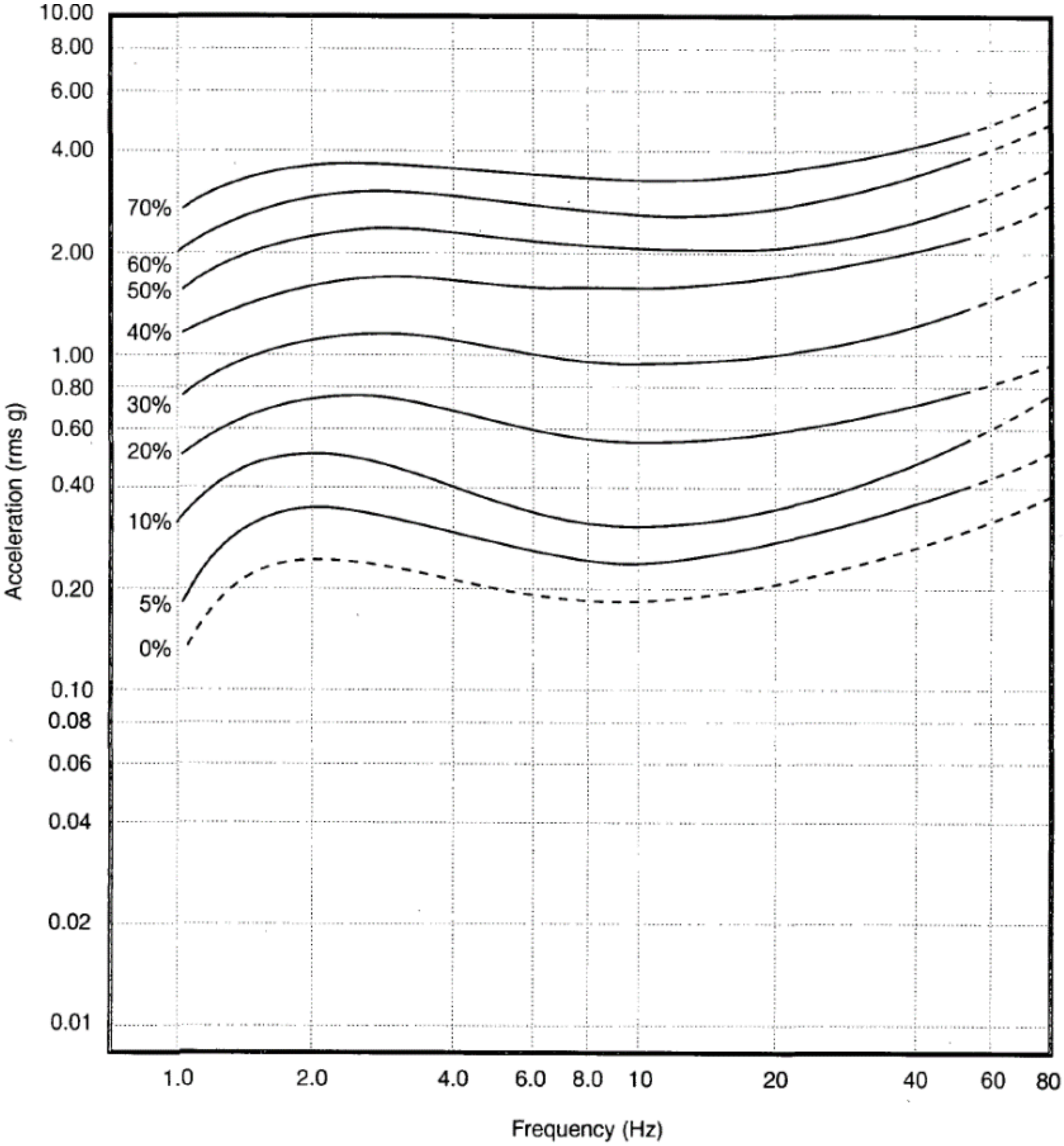

Figure 5.4 Effects on visual acuity by observed vibration characteristics (ISO in NUREG/CR-5680, Echeverria et al., 1994)

5.5.4 Manual Tracking and Fine Motor Tasks

Manual tracking (e.g., adjusting the level of a liquid using a knob), and similar behaviors where hand-eye coordination is necessary to control an object's movement can be disrupted by vibration (Lawton & Miller, 2006; Woldstad et al., 1982). Vibration frequency and acceleration are important determinants of manual tracking effects as illustrated in Figure 5.5. The broken curve in this figure shows the boundary for combinations of vibration frequency and acceleration that may be anticipated to have no appreciable effect on manual tracking. At every subsequent curve above 0 percent, the size of the target must be increased by 10 percent to maintain error-

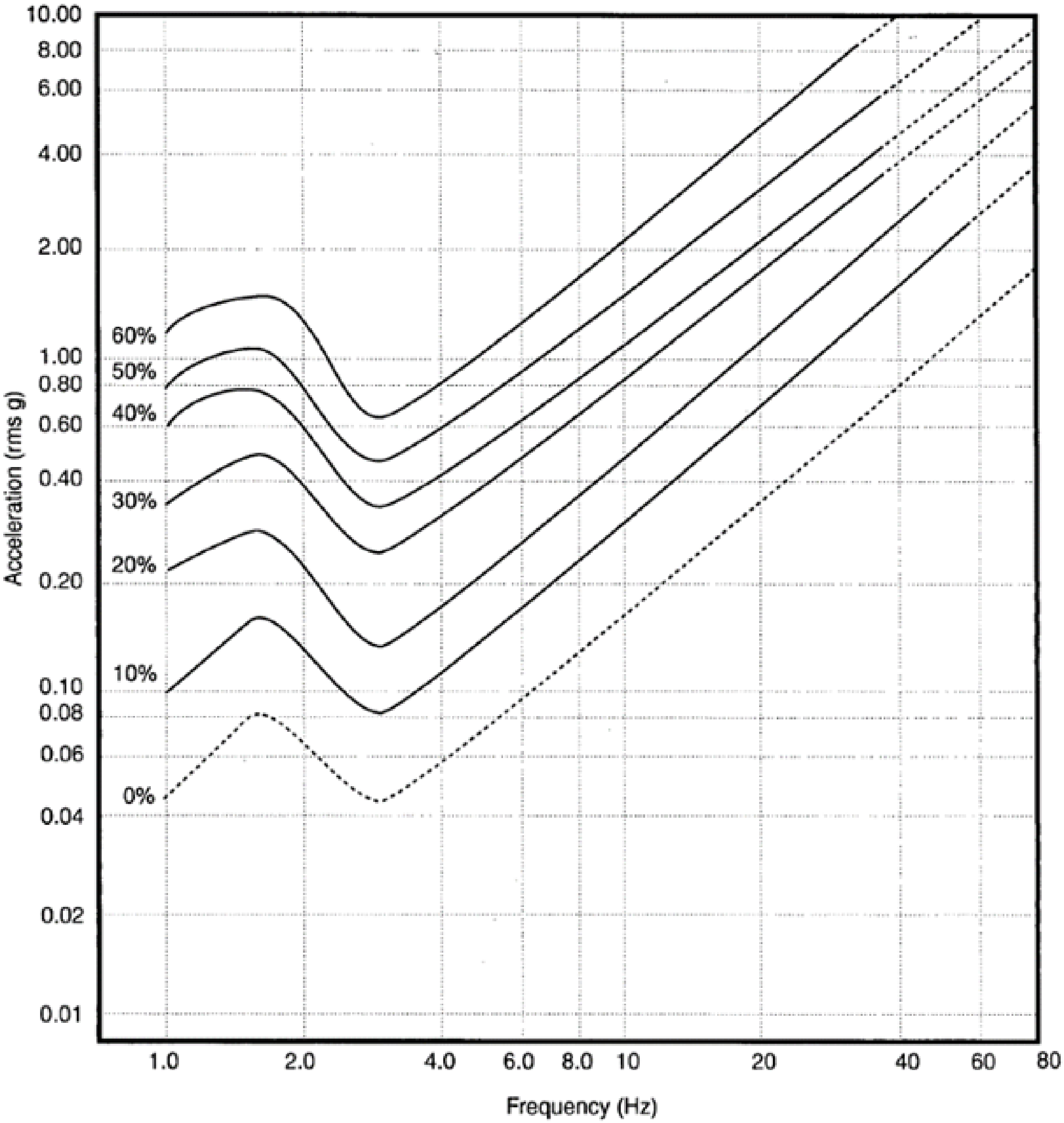

Figure 5.5 Effects on manual tracking by observed vibration characteristics (ISO in NUREG/CR-5680, Echeverria et al., 1994)

free performance. In other words, to maintain baseline manual tracking performance without error, when acceleration and frequency of the vibration fall along the first unbroken line (labeled “10%” in the figure), the size of the target the individual uses to calibrate their tracking behavior must be increased by 10 percent. Conway et al (2007) also found that fine motor tasks were negatively affected by vibration[8].

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[8] Hedge’s g = -0.84, indicating a large effect size

5.6 Potential Mitigation Measures and Their Effectiveness

A variety of approaches have the potential to reduce or eliminate the effects of vibration. As with noise, mitigation approaches include measures to reduce exposure by reducing or blocking transmission of the vibration to the worker and also by protecting the worker.

Vibration abatement and recovery strategies include the following:

- Isolate or dampen the vibration of equipment to the extent possible.
- Isolate or provide damping for workstations (e.g., energy absorbing apparatuses/materials such as shocks). Tuned mass dampers (harmonic absorbers) can be used to reduce the intensity of harmonic vibrations.
- Adapt workstations to mitigate vibration and its effects.
    - Provide larger dials and readouts (following guidance in Figure 5.5 if the acceleration/frequency remains consistent). However, very large visual displays may exacerbate motion sickness effects.
    - Provide collimated displays and redundant auditory indicators.
    - Adapt workstations and seating to stabilize worker limbs and spine.
- Limit the amount of time personnel are exposed to vibration, thereby reducing discomfort and increasing safety.
- Provide a 30-min rest break after work exposed to vibration to reduce performance after-effects.

5.7 Interactions of Vibration with Other Environmental Conditions

Vibration effects are nearly always accompanied by significant noise in practical situations (Ljungberg, 2009). Vibration may also co-occur with cold (Scheffer & Dupuis, 1989), heat, standing and moving water, and precipitation.

5.8 Summary of Research on Vibration Impacts

The state of the research addressing the effects of vibration on performance demands is summarized in Table 5.1.

Table 5.1 Vibration effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3,4	(a)
Sensation and visual recognition	1	(a) (b)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	3,4	(a) (b)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3,4	(a) (b)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	1	(a) (c)
Gross motor skills – heavy and light	4	(d)
Other neurophysiological functions	4	(a) (d)
Teamwork		
Reading and writing	2	(a) (b)
Oral face-to-face and electronic communication	3,4	(a)
Cooperation, crew interaction, command and control	3,4	(a)

Assumptions and Limitations of Applicability

(a) Higher levels of discomfort (Figure 5.3) associated with neurochemistry and cognitive processing impacts.

(b) Probability of visual acuity mistakes increases as vibration acceleration and frequency change according to Figure 5.4. This drives downstream effects on any cognitive activity requiring visual acuity (e.g., reading, memorization of items visually, computation, etc.). Adaptation is increasingly necessary (in the form of increasing target size) as vibration acceleration and frequency change according to Figure 5.4.

(c) Tracking performance disruption shown in Figure 5.5.

(d) Variety of vestibular and ocular disruptions reported (e.g., impacting standing steadiness, nausea).

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) No information (a gap).

6 LIGHTING

6.1 Introduction

During a flooding event, NPP workers may be required to perform MAs when lighting conditions are not ideal. For example, interior and exterior lighting may be lost or maintained at low, emergency levels. Sunlight may be substantially reduced by clouds and precipitation and/or nightfall. The primary effect of low or otherwise problematic light levels is to decrease the speed and/or accuracy of tasks involving visual detection and/or perception. Inadequate lighting can make some tasks very difficult to perform, especially when the task depends upon an ability to attend to smaller objects and/or objects that have low object background contrast.

Too much light can be as disruptive to the performance of MAs as too little light. The intensity of light, i.e., the amount of illuminance from light source(s), directly affects the amount of light reflected from objects in the environment (i.e., their luminance). When luminance is too intense, the resulting glare can make it difficult to perform tasks involving visual perception. Glare that completely disrupts vision is technically referred to as dazzle.

Light's spectral characteristics or the particular range (or colors) of its visible electromagnetic spectrum are also essential to certain tasks. Sunlight typically includes wavelengths across the visible spectrum, whereas artificial light can lack one or more wavelengths. For this reason, artificial light sources have the potential to either enhance or adversely affect task performance. For example, red lighting rather than full spectrum lighting enhances night vision and therefore can improve the ability of a worker to detect distant signals at night. Narrow band green light (wavelength ~530–550 nm) has been found to increase alertness and omitting light perceived as blue (wavelength <470 nm) from broad spectrum fluorescent light has been shown to reduce alertness compared to light including these wavelengths. This indicates that tasks that rely on alertness (e.g., vigilance) may suffer when shorter wavelength light is absent (e.g., Bittner, Jr. & Kinghorn, 1997; Chellappa et al., 2011). In addition, lighting with deficiencies in some wavelengths can make it difficult for workers to discriminate between colors (e.g., color coding of resistors in electronics work).

Unlike natural light, many sources of artificial light also flicker, or turn on and off very quickly (e.g., light emitting diodes [LEDs]). The frequency of flicker can affect perception, particularly when combined with movement of the light source (Wilkins & Lehman, 2010). Wilkins and Lehman also reported that flicker at frequencies >1,000 Hz can produce illness similar to motion sickness, featuring symptoms that include headaches, fatigue, and nausea. Wilkins and Lehman (2010) cautioned that long wavelength (i.e., red) LED displays may be perceived as a series of dots under vibration if their refresh rates are relatively slow (e.g., 60 Hz).

For the greatest visual acuity, light intensity should be increased in a balanced proportion relative to the intricacy of the visual task involved. Too little illuminance for the intricacy of the work will generally slow performance and cause errors due to perceptual difficulties, whereas too much illuminance will limit performance due to reflection or glare. Individual differences also affect optimal lighting conditions. For example, because of age related changes in the eye, older adults tend to require higher illumination for the same job than their younger counterparts.

Figure 6.1 provides an overview of the key attributes of lighting, as well as the extent to which each has been researched and is relevant to the performance of MAs.

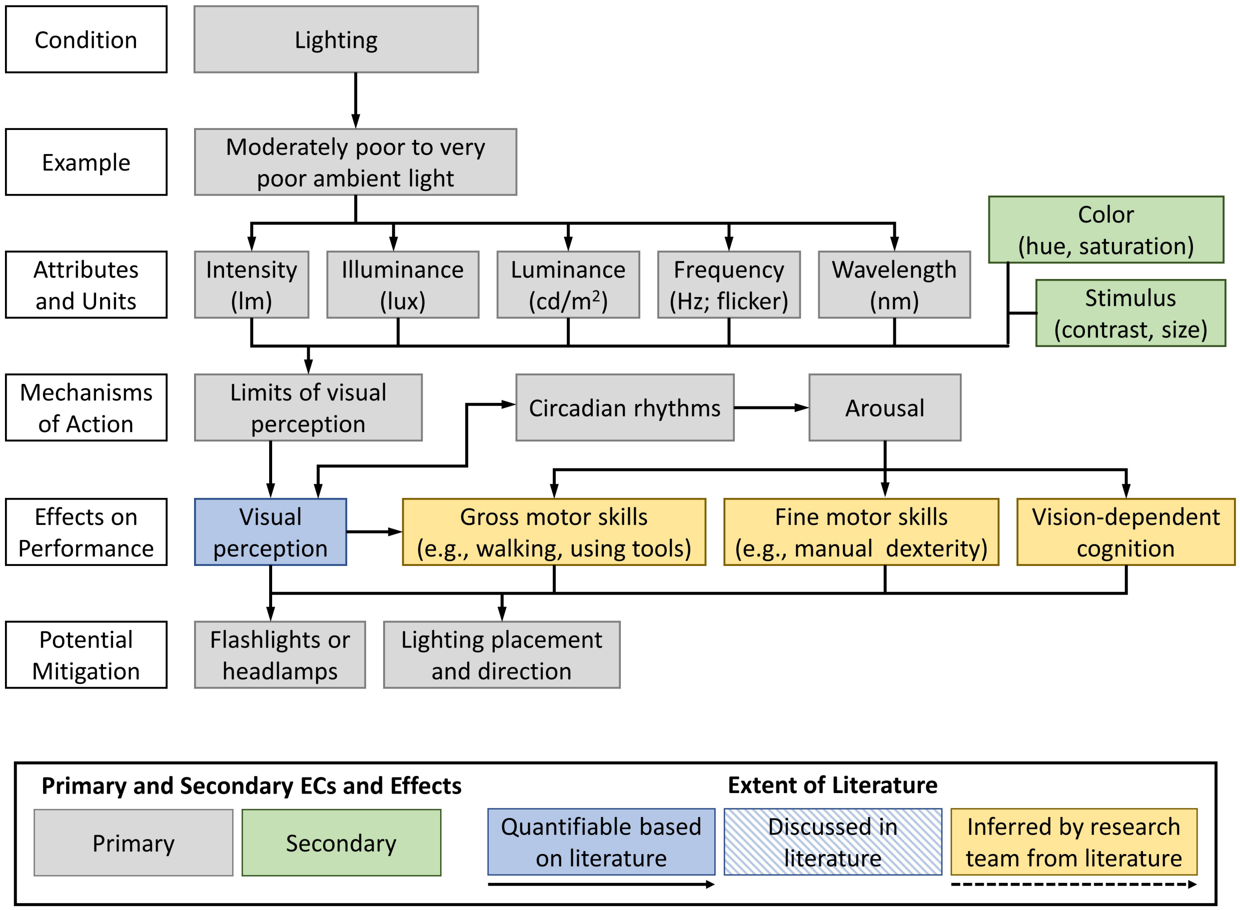

Figure 6.1 Lightning effects overview[1]

6.2 Attributes and Units of Measurement

Light, at a single frequency, can be conceptualized as a wave, which has the following characteristics:

- Frequency – is the number of waves per unit time, often measured in the number of waves that pass a point in a given time (e.g., cycles per second).
- Wavelength – is the distance between waves or cycles. For light, wavelength is measured in nanometers (nm) (or billionths of a meter).

Because frequency can be easily computed from wavelength, and vice versa[2] discussions in the scientific literature typically use one or the other exclusively. The human performance literature typically uses wavelength (nm).

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[1] Only some performance demands are listed here, as others may not be significant for the example condition.

[2] The equation that relates wavelength and frequency for light (and other electromagnetic waves) is: $\lambda v = c$ where λ is the wavelength, v is the frequency, and c is the speed of light.

The electromagnetic spectrum is an ordered description of the array of energies that photons, or particles of electromagnetic energy, can possess. The spectrum ranges from low-frequency, long wavelengths (radio waves) to high-frequency, short wavelengths (gamma rays). Visible light, as experienced by humans, is a relatively narrow range of this electromagnetic spectrum, typically between about 380 to 750 nm. As illustrated in Figure 6.2, the human eye experiences visible wavelengths as colors. For example, 620–750 nm light is experienced as red and 380–450 nm light is experienced as violet (Table 6.1). When visible light contains all these wavelengths (e.g., light from the sun), it is perceived as having no color and is called white light.

The color of an object can be described by three characteristics:

- Hue – is determined by the wavelength the surface of the object reflects when white light shines on it (or the wavelength emitted by a narrow-frequency light source).
- Saturation – is defined as the purity of the color. Saturation is determined by the bandwidth of light absorbed and reflected by the object (or narrow-frequency light source). The narrower that bandwidth, the purer, or more saturated that color is.
- Value – is the degree of lightness or darkness of the color.
- Light can be measured in several ways, some based on objective information, and others on human perception.
- Intensity (or candle power) – is the quantification of a light source's energy as radiated in all directions; it is measured in lumens.
- Illuminance – measures the degree to which an object is illuminated, or the amount of light striking the object. Illuminance is expressed in lux, where one lux is one lumen per square meter of object surface. Illuminance can also be expressed in the English unit footcandles. Illuminance is measured with a chroma meter, an illuminance meter, or an illuminance spectrophotometer.
- Luminance – The luminance of an object is based on its perceived brightness, or the amount of light emitted or reflected from the object (which is illuminated by light shining upon it) that reaches and is processed by the eye and visual apparatus. The international system unit (SI unit) for luminance is the candela (cd), a measure of luminous intensity (a common candle emits light with a luminous intensity of roughly one candela). Luminance is measured as the amount of light emitted per unit area, cd/m^2.

Electronic illuminance and luminance meters are commercially available to measure the amount of light striking and reflected from objects, respectively. Contrast and size are two additional features of a viewed object and its context that are important for visibility.

An object's contrast describes how different the luminance of the object is from its surroundings. Generally speaking, the larger this difference, the more visible an object will be. For example, in Figure 6.3, the contrast is higher for the word on the right than the one on the left.

The size of an object is also important for visibility. At a certain point, objects are too small to be seen, regardless of the light intensity or contrast with its background. Thus, a large, high-luminance, stationary object with high contrast with its background tends to be more visible, compared to an object that is small, or has low luminance, and/or low contrast.

In the United States, both indoor and outdoor lights typically operate on alternating current, which flickers as the light cycles on and off at a rate that is twice the frequency of the incoming

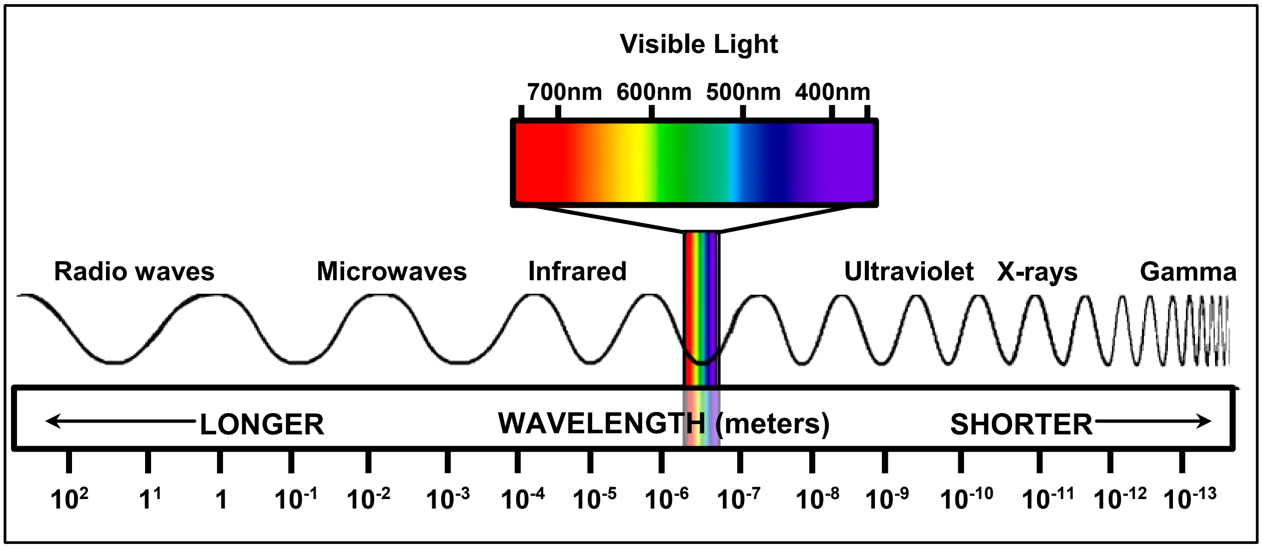

Figure 6.2 Visual representation of the electromagnetic spectrum

Table 6.1 Visible light wavelengths and subjectively experienced colors

Color	Wavelength
Violet	380–450 nm
Blue	450–495 nm
Green	495–570 nm
Yellow	570–590 nm
Orange	590–620 nm
Red	620–750 nm

Figure 6.3 Contrast example

power line (e.g., in the United States the flicker is at 120 Hz, twice the 60 Hz line frequency). Flicker can be a significant problem with some types of lighting, including certain magnetically ballasted fluorescent, metal halide, high-pressure sodium, and LED lamps (PNNL, 2012; Poplawski & Miller, 2013). Inadequate maintenance, the initial quality of the components used in the manufacture of the lamps, and/or issues with the electrical generating sources can result in detectable flicker. Workers can typically detect flicker below ~50 flashes per second (50 Hz)[3].

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[3] This is consistent with the point at which individual sinusoidal flickers cannot be distinguished at typical light levels, as discussed in the context of Figure 6.7.

6.3 Time Variation of Light

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to severely diminished light. More importantly, because the light levels during a flood may change, personnel exposure to this EC may also be variable in time. In other words, the severity of diminished light is time dependent and may vary significantly over the duration of execution of a manual action or task.

Figure 6.4 is a hypothetical ambient light level plot, illustrating both broad trends in lighting variability as it might occur during a flooding event and periods during which three MAs may be performed. On top of this trend, intermittent supplementary lighting may increase that shown (e.g., spot- and head-lamps) and blocking the ambient source (e.g., working within a tented shelter to escape wind or other adverse ECs or working in the shadow cast by equipment) may decrease it. The type and level of lighting available during the conduct of the MAs can affect the time and accuracy with which they can be performed.

6.4 Mechanisms of Action

Lighting affects MAs as a consequence of the characteristics and limitations of human visual perception and the interaction of light with the body's circadian rhythms.

6.4.1 Limits of Visual Perception

The effect of lighting on performance is related to limits of visual perception, as shown in Figure 6.5. For example, when the luminance of an object is less than 3.426 × 10-6 cd/m^2, light stimulus is insufficient to activate the retina's rod (low light) receptors, thus preventing perception of the stimulus (Grether & Baker, 1972). At luminance levels just above this threshold, the achromatic (colorless) rod receptors or rods are activated, and vision becomes possible, but contrast remains low and color vision is completely absent (until light levels increase sufficiently to activate the cones, receptors that provide color perception). At these low luminance levels, activities requiring discrimination of information from its background (e.g., reading signs, writing, driving) will be slowed and prone to error, and discriminations based on color (e.g., discriminating warning red coloration from green) will be impossible without secondary, non-color cues (e.g., octagonal stop shape).

Both rods and cones are active within the range of illumination levels between moonlight and those expected for average indoor, electrically lit environments. Visual acuity and color vision are ideal near the top of this range. In illuminance conditions of intense, direct sunlight and higher, where reflectance from viewed objects is high (i.e., glare), so much light can reach the cone cells that they become fatigued, bleaching the receptors' photopigments occurs (Hood & Finkelstein, 1986), and visual perception is disrupted. Further exposure at this level of light intensity can damage the retina and other eye structures (e.g., snow blindness).

6.4.2 Circadian Rhythms

Exposure to intense light (compared to exposure to less intense light or darkness) reduces melatonin levels, reduces associated subjective sleepiness, and increases alertness (Cajochen et al., 2014; Comperatore et al., 2015; Smith & Eastman, 2012). Chellappa et al. (2011) have shown that blue enriched light significantly increases speed on sustained attention tasks. On the other hand, blue enriched light is contraindicated when night vision is important (e.g., Bittner, Jr. & Kinghorn, 1997, regarding inappropriateness of blue augmentation where external

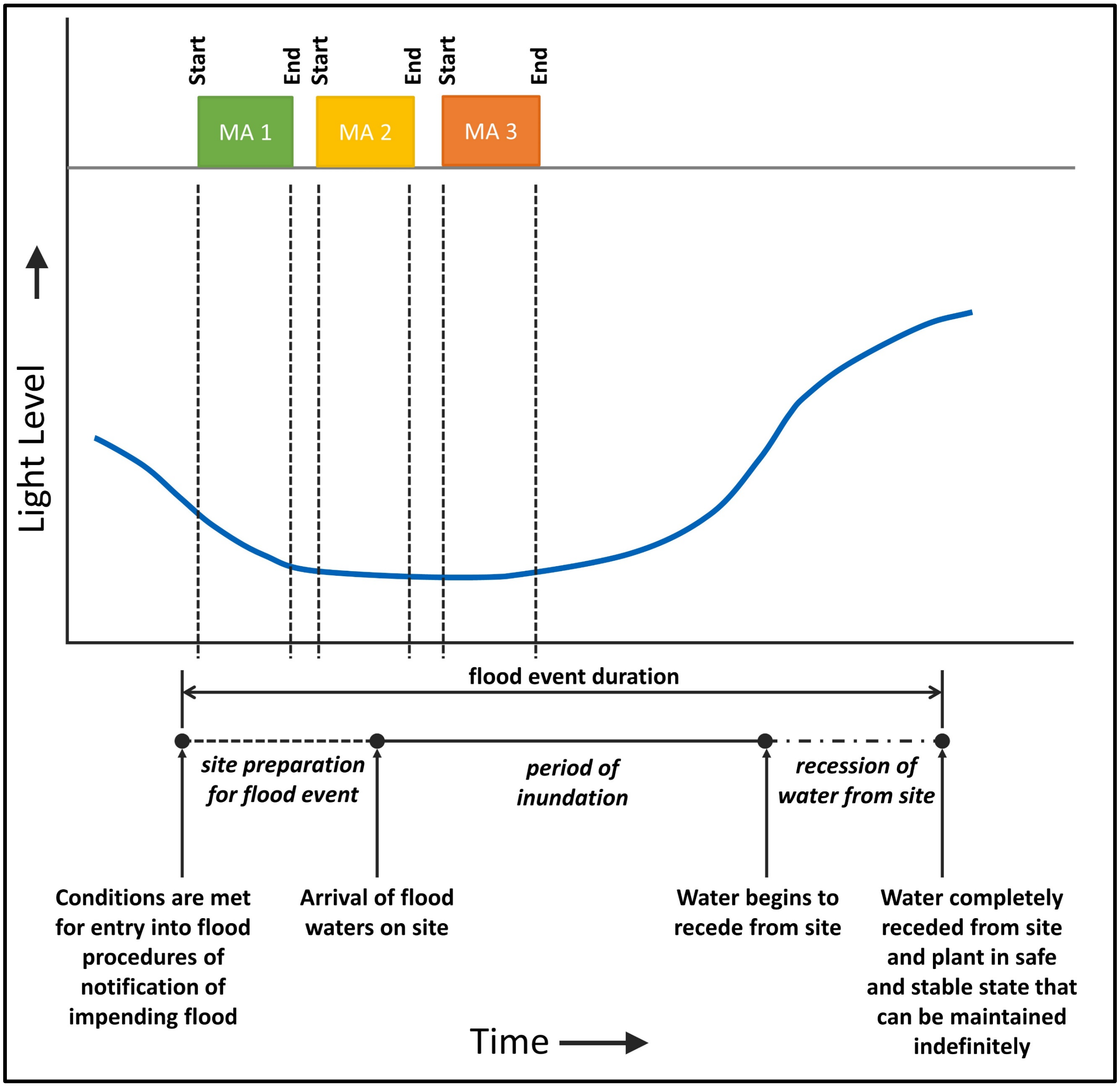

Figure 6.4 An illustration of light variation during an example of a hypothetical flooding event

watchkeeping is critical). Consequently, identification of a prospectively ideal alerting spectrum depends on both the nature of the immediate task and the requirements for the tasks that follow. The mechanism of these arousal-based effects appears to involve the body's circadian system, the apparatus governing human sleep wake cycles and time-of-day effects on performance (e.g., Krishnan & Lyons, 2015). This mechanism may be partly responsible for the observed improvements in worker performance demonstrated with full spectrum office lighting and with green- and blue-augmented lighting systems (e.g., Begemann et al., 1977; Cajochen et al.,

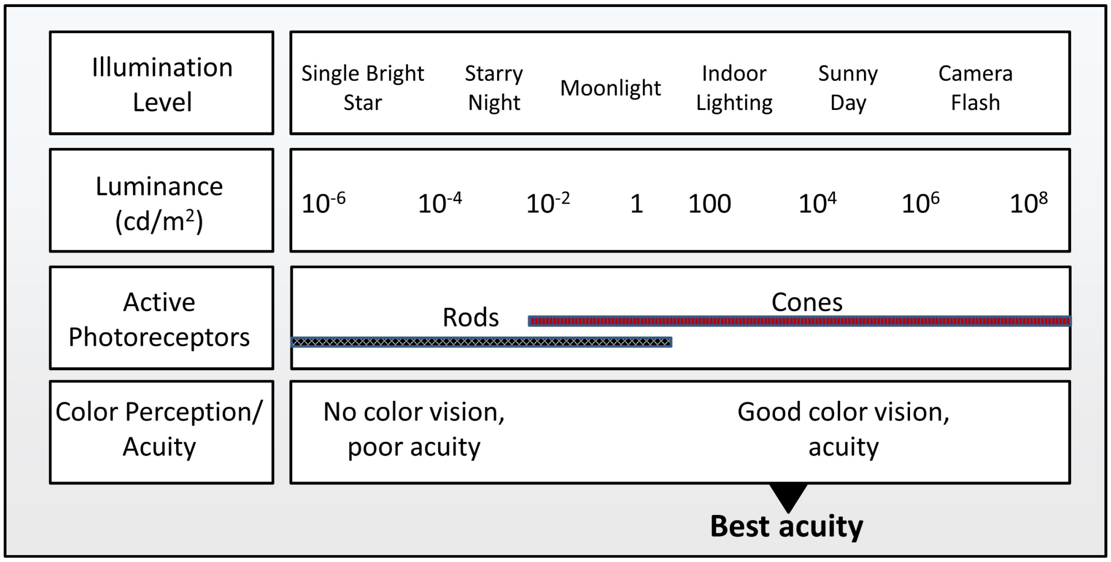

Figure 6.5 Visual perception response at different illumination/luminance levels (after Hood & Finkelstein, 1986)

2014; Comperatore et al., 2015; Edwards & Torcellini, 2002; McColl & Veitch, 2001; Smith & Eastman, 2012)[4].

6.5 Effects on Performance

Lighting has been shown to affect visual performance, perception of color, reading and writing, visual inspections, alertness, and gross motor task performance.

6.5.1 Visual Performance

The quality and intensity of light can profoundly affect visual performance and any downstream physical or cognitive tasks that depend on vision. On the one hand, very intense, highly focused light, or light with particular spectral energy characteristics, will initially disrupt night vision, which might be important to outside work in unlighted conditions (e.g., nominal interior overhead lighting may be disruptive for 15–20 min). Sufficiently intense light can damage the retina, causing temporary, if not permanent, vision loss. In this regard, intense ultraviolet (UV) light (e.g., associated with unprotected arc welding) can blind in the short term and cause cataracts in the longer term (Roberts, 2011). The photo oxidative damage associated with such conditions is caused when the light produces reactive oxidative molecules that cause damage to retinal tissues. On the other hand, when luminance is low (<3.426 × 10-6 cd/m^2; Grether & Baker, 1972), objects cannot be seen at all, because the intensity is not sufficient to even activate the light receptors in the eye. For activities performed above this actuation threshold, the IES provides recommended luminance levels, depending on the particular task. These are shown in Table 6.2.

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[4] Narrow band blue light (~480 nm) activates a third type of photoreceptor (along with rods and cones) that may provide a means for visual perception at illumination levels well below those typically provided by conventional light sources (see Alkozei et al., 2016; Berson, 2003). In addition, green (~540 nm) light might be as effective as blue light when pupillary responses are considered (Comperatore et al., 2015). This is noted here because it relates to mechanisms of action, despite the fact that it is not seen as particularly pertinent regarding flooding conditions

Outdoor daytime illuminance ranges from between 1,000 to 2,000 lux for a typical overcast day, to 120,000 lux or more for the brightest, un-occluded sunlight. Thus, as seen in Table 6.2, outdoor lighting is sufficient on overcast days to perform most tasks that do not require discrimination of small size, low contrast objects. When the task is more difficult (e.g., smaller in size, lower in contrast, or involves longer time-on-task) or when it takes place in the shade or a location affected by shadows, supplementary lighting may be required to assure error-free, timely task completion. Extreme daytime storms can occasionally reduce illuminance to around 1 lux, about the equivalent of a clear night with a full moon. Such low-light conditions would require supplementary lighting to conform to IES guidance.

The positioning of supplementary lighting is important to performance and safety. The location and directionality of the supplementary lighting, for example, can cast shadows that conceal hazards and potentially cause accidents (e.g., trips and falls). Although supplemental lighting may aid work at the point of focus, if poorly positioned it may create deleterious glare for other workers. Glare may also arise from natural sunlight, of course, and natural sunlight may even exacerbate the glare of supplemental lighting.

Whatever the source, glare from excessive or poorly positioned illuminance reduces contrast between targets and surroundings, and thus can increase visual perception task time and/or errors. The discomfort associated with glare from interior lighting can be quantified through IES's discomfort glare rating approach[5]. This approach takes into account room size; reflectance of surfaces; illumination; number, type, and size of lights; and the color rendering index (CRI) of each; observer location and age; and the type of objects in the room (e.g., furniture, equipment). As noted by the IES, this measure can be further converted into a visual comfort probability, which describes the proportion of the population that would feel the glare level was comfortable, even at the most disadvantageous position in the room. The minimum IES standard for visual comfort probability is 70, below which the amount of glare is considered unacceptable.

Table 6.2 Recommended illumination by activity

Type of Activity	Range of Illuminance (lux)
Public spaces with dark surroundings	20-30-50
Simple orientation for short, temporary visits	50-75-100
Working spaces where visual tasks are only occasionally performed	100-150-200
Performance of visual tasks of high contrast or large size	200-300-500
Performance of visual tasks of medium contrast or small size	500-750-1000
Performance of visual tasks of low contrast or very small size	1000-1500-2000
Performance of visual tasks of low contrast or very small size over a prolonged period	2000-3000-5000
Performance of very prolonged and exacting visual tasks	5000-7500-10000
Performance of very special visual tasks of extremely low contrast and small size	10000-15000-20000

Source: Illuminating Engineering Society; DiLaura et al., 2011

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[5] See the IES Lighting Handbook: Reference and Application (DiLaura et al., 2011) for the procedure. Displays.

Finally, visual perception can be adversely affected by light flicker (also known as strobing). At flicker frequencies above about 50 Hz, light sources appear to be constantly on, with no flicker[6]. However, near the flicker fusion frequency, objects moving rapidly through the visual field (due to movement of the head and/or the object[7]), may be lit at or about the same position during each flicker. This can make objects appear to be moving slower than they are, or even appearing to be stationary, if the object is cycling or rotating at the same rate (or a multiple) as the flicker. This effect is occasionally employed to assess the speed of rotational shafts. Strobe lighting has also long been used to break human and scene movement into short, apparently static images. Flicker can produce a variety of deleterious effects, many of which are very similar to motion and other perceptual conflict illnesses (see Wilkins & Lehman, 2010), including the following:

- neurological problems, including epileptic seizure
- headaches, fatigue, blurred vision, eyestrain
- migraines
- reduced visual task performance
- apparent slowing or stopping of motion (stroboscopic effect), which can be a significant safety hazard if someone mistakenly believes high-speed equipment is moving slowly or is stationary
- distraction.

These effects can be exacerbated by the following:

- duration of exposure (longer is worse)
- area of the retina receiving stimulation (greater is worse)
- location in visual field (central is worse because it projects to a greater area of the visual cortex)
- brightness of the flash (higher luminances are worse; photopic [involving retinal rod receptors] light produce higher risk)
- contrast of the flash with background (higher is worse)
- color contrast of flash (deep red is worse).

6.5.2 Color Perception

Basic color perception, which is used in distinguishing color coding of wires, for example, requires that the viewed object is perceived to exhibit a minimum luminance of at least 3 cd/m^2 (Brown, 1951). Below this luminance level, the cone receptors of the retina give way to rods, which specialize in low light vision and cannot discriminate color. Above this minimum, color discrimination relies primarily (apart from individual differences in color perception due to age or other factors) upon (1) the color output (or chromaticity) of the light illuminating the colored surface (Thornton, 1973), and (2) the reflectivity (luminance) of that surface. Color perception ratings for lighting of different types have been quantified in various ways. For example, the

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[6] Displays and light sources operating at slightly different refresh/cycle rates by design or maintenance issues have been informally shown to induce an apparent peripheral rolling motion at rate of the difference, with similar deleterious effects (nausea, etc.).

[7] Such as a rotating wheel.

CRI, developed by the Commission Internationale de l'Éclairage (CIE), measures the ability of humans to distinguish different colors using a given light source (see Table 6.3). A CRI of 100 reflects ideal color discrimination. Errors in distinguishing among colors are uncommon above a CRI of 80. As can be seen in the table, mercury and sodium lamps provide the worst CRIs, whereas simulated daylight fluorescent lamps provide among the best.

6.5.3 Reading and Writing

Illuminance levels and associated outcomes (e.g., glare) have long been found to affect both reading and writing. For example, Tinker (1939) examined the effects of lighting at different illuminances on reading speed for high contrast text. Little improvement in speed for this task was observed above 100 lux, but the author recommended levels of 200–300 lux for finer discriminations (e.g., smaller fonts and/or reduced contrast). This 100-lux plateau for reading under ordinary conditions was later confirmed by Weston (1945, 1953), who also replicated the observation that as targets were reduced in size, increasing illumination up to about 1,000 lux improved reading speed and accuracy, after which improvement plateaued again.[8].

Table 6.3 Color and color rendering characteristics of common light sources

Test Lamp Designation	CIE General Color Rendering Index (CRI)*
Fluorescent Lamps	
Warm white	52
Warm white deluxe	73
White	57
Cool white	62
Cool white deluxe	89
Daylight	74
Three-component A	83
Three-component B	82
Simulated D_{50}	95
Simulated D_{55}	98
Simulated D_{65}	91
Simulated D_{70}	93
Simulated D_{75}	93
Mercury, clear	15
Mercury, improved color	32
Metal halide, clear	60
Xenon, high-pressure arc	94
High-pressure sodium	21
Low-pressure sodium	44
DXW tungsten halogen	100

CIE = Commission Internationale de l'Éclairage

Source NUREG/CR-5680, Echeverria et al., 1994

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[8] The higher values are also reinforced by studies showing worker visual contrast sensitivity differences for text at lower contrast values (albeit contemporary testing would be recommended to avoid possible issues).

Inadequate lighting has been shown to increase the time taken to complete other simple, practical tasks that have strong visual components. Bennett et al. (1977), for example, had participants engage in manual note taking, needle probing, and micrometer reading tasks at a broad range of illumination levels (see Figure 6.6). Almost uniformly, completion speeds for these tasks began to asymptote at between 50 and 200 lux, an outcome very similar to earlier studies (e.g., Tinker, 1939; Weston, 1945, 1953). Therefore, generally speaking, lighting lower than 50 to 100 lux is likely to slow simple visual task speed in average workers. The word average should be stressed here, however, because individual differees (e.g., worker age) can be strong mediators (e.g., Smith & Rea, 1978). Thus, adaptations of lighting for maximal performance should consider the problem at the group level but provide flexibility to accommodate individual needs (i.e., individual work lamps, work instructions/reports printed in larger fonts, etc.).

6.5.4 Visual Inspections

A common requirement in NPP licensees during and after storms and other flooding events is visual inspections. Such inspections could include a visual search of an object or area for damage or defects (e.g., damages to premises, equipment, and safety measures). These tasks often rely heavily on the amount and quality of lighting present, especially at night or during black-out conditions. Illumination guidelines for detection of damage/defects range between 500 and 2,000 lux (see Table 6.4). These levels tend to be well above the average office workplace illumination range of 300–500 lux. However, the lighting requirements for any given inspection task depend heavily on the target defects themselves (e.g., size, shape, distinctiveness [contrast], etc.), and the visual clutter in the area to be inspected. For example, when inspecting broad, continuous areas at a distance for problems, diffuse lighting tends to be most useful. However, when performing finer inspections close up (on the order of around 24 inches), more directional lighting can facilitate detection of finer defects (as suggested by See, 2012). Insufficient illumination is likely to increase the amount of time needed to visually inspect an area or item for defects and reduce defect detection rates. In high-risk situations, under poor illumination workers are likely to adopt a conservative decision bias, which may increase detections, but will also increase false alarms.

The effects of inadequate illumination, including increased time and more errors, also affect the quality of downstream information processing and any associated manual processes. As a rule, the greater the contribution vision makes to the performance of a given task, the larger the adverse effects of inadequate lighting will be. The guidelines in Table 6.4 may therefore also serve as a basis for assessing time and error effects on downstream information processing and motor tasks. For example:

- Manually building a circuit by soldering small electronic components to a small breadboard, as interpreted from a blueprint/circuit diagram, is equivalent to a visual task of small size and low contrast over a prolonged period (from Table 6.2). Therefore, if the lighting for this fine motor skills task is less than 2,000 lux, we should expect one or more of the following: an increase in time required to complete the task, fine motor errors, and errors in interpreting the blueprint (understanding and noticing).
- Noticing and reacting to a hazard in the path of a forklift under poor lighting conditions requires that the visual system be able to perceive the object. From Table 6.2, this arguably begins with a visual task of low contrast (the hazard and its surroundings under poor lighting conditions). If the object's salience is not made evident because lighting is inadequate (in this case, under 1,000 lux), it may go undetected. If undetected, no

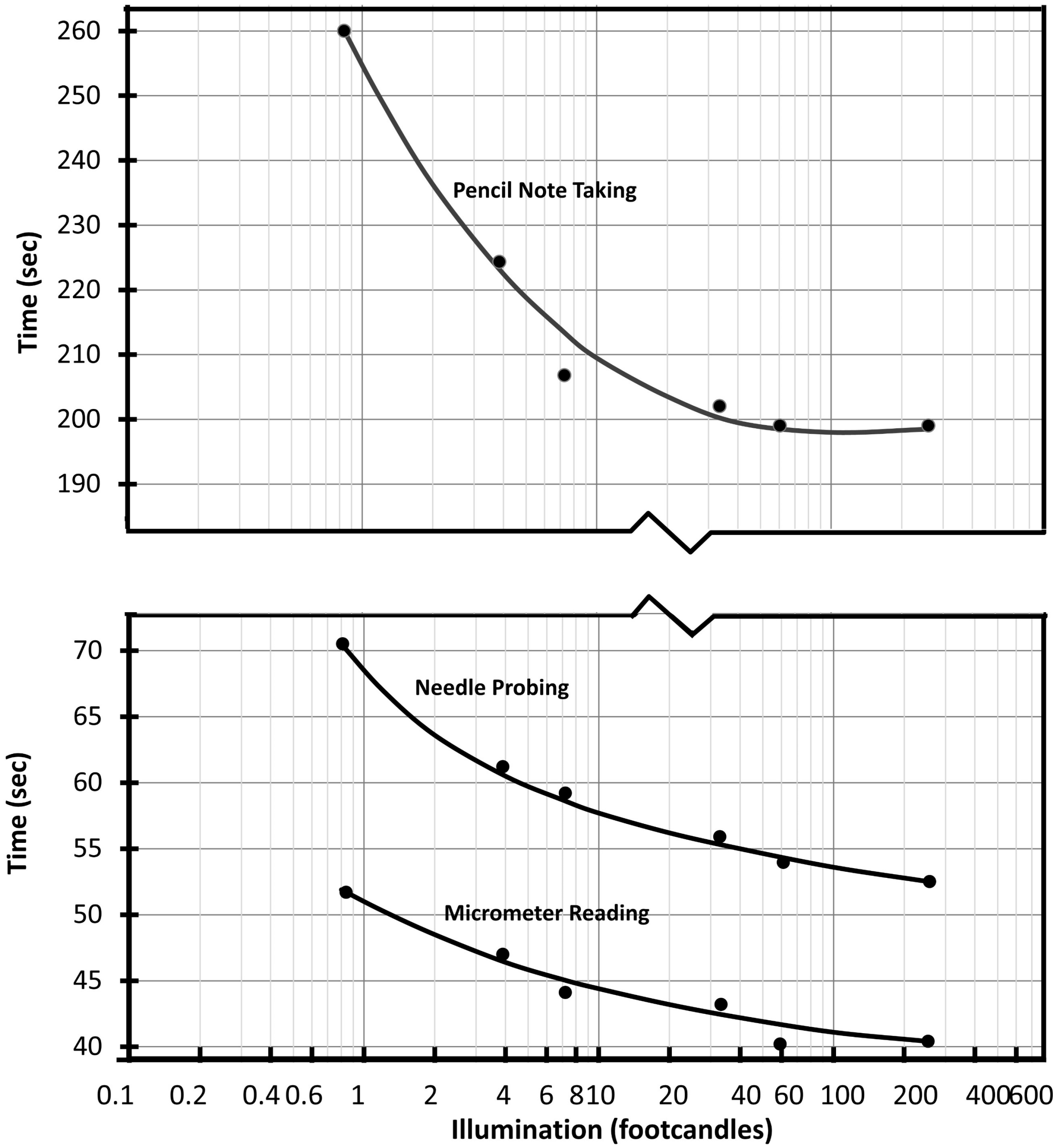

Figure 6.6 Relationship between illumination and task completion time (NUREG/CR-5680, Echeverria et al., 1994)

continuous (reactive steering) or discrete (braking to a halt) fine motor skills would be engaged to avoid it.

Glare and/or insufficient lighting have the potential for adverse cross modal effects, although there is no consensus about the specific mechanisms by which this occurs (e.g., Sabri et al., 2014; Sörqvist et al., 2016). When tasks are complex, degraded perceptual information quality may push the already taxed processing apparatus into an overloaded state in which the worker must apply all surplus resources to maintain good performance on the task. This can leave few or none to monitor other modalities, such as hearing (Sörqvist et al., 2016). Using our circuit

Table 6.4 Illuminance guidelines for inspection tasks by difficulty

Inspection Difficulty	Illuminance Guidelines
Ordinary	500 lux
Difficult	1000 lux
Highly Difficult	2000 lux

Source: See 2012

building example, if the task is made even more difficult by inadequate lighting (or glare), the ability to listen for the reminder chime from a computer may be degraded. This failure to notice the auditory cue could cause the individual to neglect another essential task.

6.5.5 Alertness

Lighting that is inadequately bright or is lacking certain spectral characteristics can result in decreased alertness, compared to brighter light or light that has spectral characteristics similar to sunlight (Badia et al., 1991; Lafrance et al., 1998). Because of this, full spectrum fluorescent lighting has enjoyed preferential treatment in office environments to increase arousal and decrease fatigue (McColl & Veitch, 2001). However, this full spectrum preference has been subject to considerable scrutiny and refinement. Further study of the effects of light intensity suggests that illuminances between 100 and 1,000 lux represent the plateau of the effect of intensity (see Cajochen, 2007). These studies have also shown that light above 1,000 lux may not only produce no further improvement in alertness, but the associated glare may lead to the opposite effect. Discovery that retinal-ganglion cells contain photopigments responsive in the blue range of light (Berson, 2003) led to studies showing that light of short wavelengths (~530 550 nm green, if not ~470 nm blue) produces greater subjective and objective measures of alertness than full spectrum lighting (Cajochen et al., 2014; Chellappa et al., 2011; Comperatore et al., 2015; Smith & Eastman, 2012).

The alertness encouraged by higher intensity and short wavelength light has been shown to enhance the performance of a variety of cognitive tasks. These include positive effects on laboratory tasks requiring sustained attention (Psychomotor Vigilance task, Beaven & Ekström, 2013; Chellappa et al., 2011) and working memory (N-back task, Alkozei et al., 2016)[9]. Benefits over regular lighting have been observed in naturalistic settings as well, including improved processing speed and concentration improvements in high school students (Keis et al., 2014) and improved subjective mood and well-being in office environments (Borisuit et al., 2015).

6.5.6 Gross Motor Tasks

Both insufficient and excessive illuminance can negatively affect performance of gross motor tasks, increasing the time required to complete them and/or increasing errors. For example, if illuminance is too low during a trench digging task, workers may slow down to assure that the tool is placed correctly (e.g., shovel placement, stroke depth). Under time pressure (e.g., as might occur from an impending storm), inadequate tool placement could cause inaccurate outcomes (e.g., depth, level, etc.) and increase the probability of accidents (e.g., impacting one’s foot with the shovel).

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[9] These effects persist immediately following cessation of the experimentally enhanced lighting, and then tend to slowly decline (typically~30 min after melatonin increases).

6.5.7 Recommended Limits

Most normal work environments will not produce light that has characteristics likely to produce any type of damage to the eye or its structures. In these cases, adhering to the lighting recommendations for specific tasks involved (see Table 6.2) will keep workers well out of the range of eye damage. Certain jobs, however, like welding, may expose workers to intense UV-A (315 nm to 400 nm) and UV-B (280 nm to 315 nm) light. Appropriate protective eyewear can be worn to counter any negative effects of this light.

As discussed in Section 6.5.1, flicker from light sources can cause motion sickness–like effects. To avoid this, the Institute of Electrical and Electronics Engineers (IEEE) has produced standards for lighting's flicker effects based on the frequency and modulation characteristics of the light (see Lehman & Wilkins, 2014). Figure 6.7 plots data from multiple studies in which participant perception of the stroboscopic effect (not necessarily actual symptoms) was quantified as a result of light at different frequencies and modulation (flicker) percentages. Using these, Lehman and Wilkins (2014) identified ranges at which no effect and low probability of flicker effects may be anticipated. According to the graph, lights with frequencies above 1,000 Hz should be reasonably unlikely to produce performance effects.

6.6 Potential Mitigation Measures and Their Effectiveness

As described above, the lighting conditions under which performance is most likely to be degraded are those in which there is too little or too much light, and possibly light that has less than optimum spectral characteristics. When too little or too much light is a problem, the best solution is to increase or decrease the local illuminance accordingly. In most office and sheltered environments, maintaining light intensities between 100 and 1,000 lux will provide adequate light for most common tasks. However, as tasks become more intricate and require resolution among small items, lighting should be increased (see Table 6.4). Similarly, problems caused by poorly directed light are best addressed by adjusting, supplementing, or blocking the light to remove shadows or glare.

Too much light affects performance primarily through glare. To reduce direct glare from lights several steps can be taken, as follows:

- Use lights with low discomfort glare ratings.
- Lower the luminance (reflected light) of lights by using more low-intensity lights instead of fewer high-intensity lights.
- Locate lights as far away from the worker's line of vision as possible.
- Increase the luminance around a glare spot to lessen the brightness ratio.
- Install barriers (e.g., hoods, visors, or shades) to shield glare spots.

To reduce reflected glare from surfaces, take the following steps:

- Keep luminance levels as low as possible.
- Provide good illuminance levels.
- Use diffused lighting.
- Position lights so that reflected light cannot enter directly into the workers' eyes.

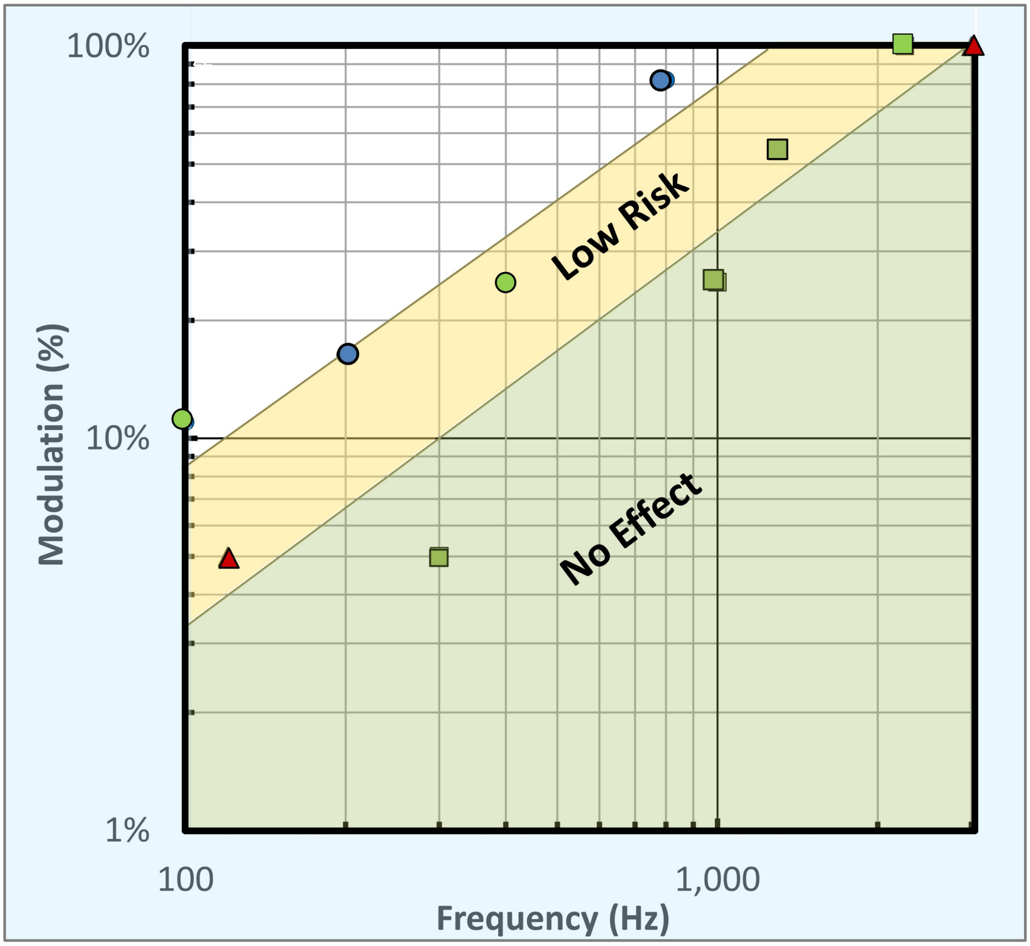

Figure 6.7 Summary of flicker effects from multiple studies (adapted from Lehman & Wilkins, 2014). The low-risk (orange) and no-observable-effect (green) regions for flicker as a function of the frequency and modulation percentage. The line Mod% =0.0333*$f_{flicker}$ separate the no-observable-effect and low-risk regions, and the upper margin of the low-risk region is given by the line Mod% =0.08*$f_{flicker}$.

- Use matte surfaces to reduce reflectance.
- Reduce glare on computer monitors or controls/readouts by using polarized screens.

When lighting interventions are considered, the potential for individual differences should be kept in mind. Older workers, for example, tend to need higher illuminance for the same job than younger workers because of age related changes in the eye.

Because spectral characteristics of light affect color perception, night vision, and alertness, matching the quality of the lighting attention to the quality of lighting has recently been shown to be important to alertness and attention. Lighting should be chosen that does not neglect visible wavelengths under 470 nm. Further, if color perception and discrimination are essential to task performance, lamps with a CRI approaching 100 (e.g., simulated daylight fluorescent lamps) should be considered. Finally, lamps with higher frequencies (e.g., above 1,000 Hz) could be recommended to avoid flicker sickness symptoms (see Figure 6.7).

6.7 Interactions of Lighting with Other Environmental Conditions

Lack of adequate lighting may co-occur with precipitation, standing and moving water, and heat or cold during storms. Lightning flashes can cause visual dazzle effects, and ice and snow may produce glare when reflecting high intensities of light.

6.8 Summary of Research on Lighting Impacts

The state of the research literature addressing the effects of lighting on performance demands is summarized in Table 6.5.

Table 6.5 Lighting effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	2,4	(a)(b)(c)(d)(e)
Sensation and visual recognition	2	(a) (c) (b)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	2,4	(a) (b) (c) (d)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	2,4	(a) (b) (c) (d)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	2	(a) (c) (d)
Gross motor skills – heavy and light	2	(a) (c) (d)
Other neurophysiological functions	2,4	(a) (d)
Teamwork		
Reading and writing	2,4	(a) (b) (c) (d)
Oral face-to-face and electronic communication	2,4	(a) (b) (c) (d)
Cooperation, crew interaction, and command and control	2,4	(a) (b) (c) (d)

Assumptions and Limitations of Applicability

(a) When luminance of a to-be-seen object is less than 3.426 × 10-6 cd/m^2, not enough light is present to activate retinal receptors, thus, visual perception cannot occur. This is a general minimum for any downstream action or cognitive ability requiring vision. Similarly, when luminance is greater than about 107 cd/m2, vision becomes impossible because of dazzle, glare, or ultimately temporary bleaching of retinal receptor photopigments.

(b) Any task requiring color perception will be impossible below a luminance of 10-2 cd/m^2. This is a general minimum for any downstream cognitive ability requiring color perception. Basic color perception, such as distinguishing color coding, requires object is perceived to exhibit a minimum luminance of at least 3 cd/m2.

(c) The effects on tasks requiring vision to complete will depend heavily on the details of the task - see Table 6.4.

(d) Light characteristics (e.g., flicker frequency, spectral characteristics/color rendering index, location, and size) can be strong determinants of task performance, depending on the particular mix of performance demands making up a task. Lab research effects tend to be on very controlled tasks and lighting characteristics types, which makes generalization to externally valid tasks difficult.

(e) Exposure to light with specific blue and/or green spectral characteristics may improve certain tasks that are prone to alertness effects.

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) No information (a gap).

7 HUMIDITY

7.1 Introduction

Humidity is defined as the amount of water vapor in the air.[1] Humidity affects how workers perceive objectively measured temperatures. High humidity can make temperatures feel either hotter or colder than they are. As an EC associated with flooding events at NPPs, high humidity is commonly experienced in large portions of the United States. This is particularly true near waterbodies both during and after precipitation with or without significant flooding. The standing water associated with flooding can increase local humidity levels. It can become a significant factor in both outdoor and indoor work environments. Humidity is generally accepted as an important ambient environmental measure identified in job risk factors associated with heat stress (Bernard & Iheanacho, 2015). However, its distinct contribution to psychological and behavioral effects is not well studied. Rather, humidity is typically addressed as a component of combined, perceived heat metrics (e.g., WBGT, effective temperature index.[2]), which always include one or more temperature measures (e.g., air and/or radiant temperature). These metrics may also include other mediating variables (e.g., air movement, cloud cover, and sun direction).

Humidity affects comfort. High humidity causes discomfort, especially when ambient temperatures are high. Very low humidity can also cause discomfort, especially when combined with wind, which can dry out eyes and mucus membranes. At the same temperature, higher humidity is related to both reduced heat tolerance and higher subjective discomfort. This is attributed primarily to high humidity's tendency to slow the body's ability to lose heat through evaporation at the skin surface. Water resistant protective clothing aggravates this tendency (see also Chapter 2, Heat). Conversely, cold air with high relative humidity feels cooler to humans and is more likely to cause discomfort and decrease cold tolerance than drier air of the same temperature. This is because high humidity tends to increase the conduction of heat from the body (see also Chapter 3, Cold).

Water vapor begins to condense out of the surrounding air when relative humidity approaches 100 percent (or its dew point).[3]. Condensation can fog eyewear, displays, and vehicle windshields, making visual tasks difficult or even dangerous. Through condensation, high humidity can make tool handles slippery and cause surfaces like pavement and grass to become slick, slowing progress and increasing the probability of accidents (e.g., slips and falls). The hazard associated with condensation can become substantial when air temperature drops below freezing and the condensation forms a glaze of ice on damp surfaces. These various forms of condensation generally slow progress and increase the probability of accidents. Humidity effects are typically incorporated into humans' experience of heat and cold (see the chapters on heat and cold for more detailed performance effects. Figure 7.1 provides an overview of the attributes of humidity as well as the extent to which they have been studied and their relevance to MAs.

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[1] Relative humidity is the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature.

[2] Effective temperature is a single figure index reflecting the sensation of warmth that considers the combined effects of temperature, humidity, and wind.

[3] The dew point (dew point temperature or dew point) is the temperature at which dew forms and consequently is an alternative measure of atmospheric moisture (NOAA, 2009). It is the temperature to which air must be cooled at constant pressure and water content to reach saturation (i.e., 100 percent relative humidity). A higher nominal dew point indicates more moisture in the air. Frost point is the dew point when temperatures are below freezing and the condensation is frost rather than dew.

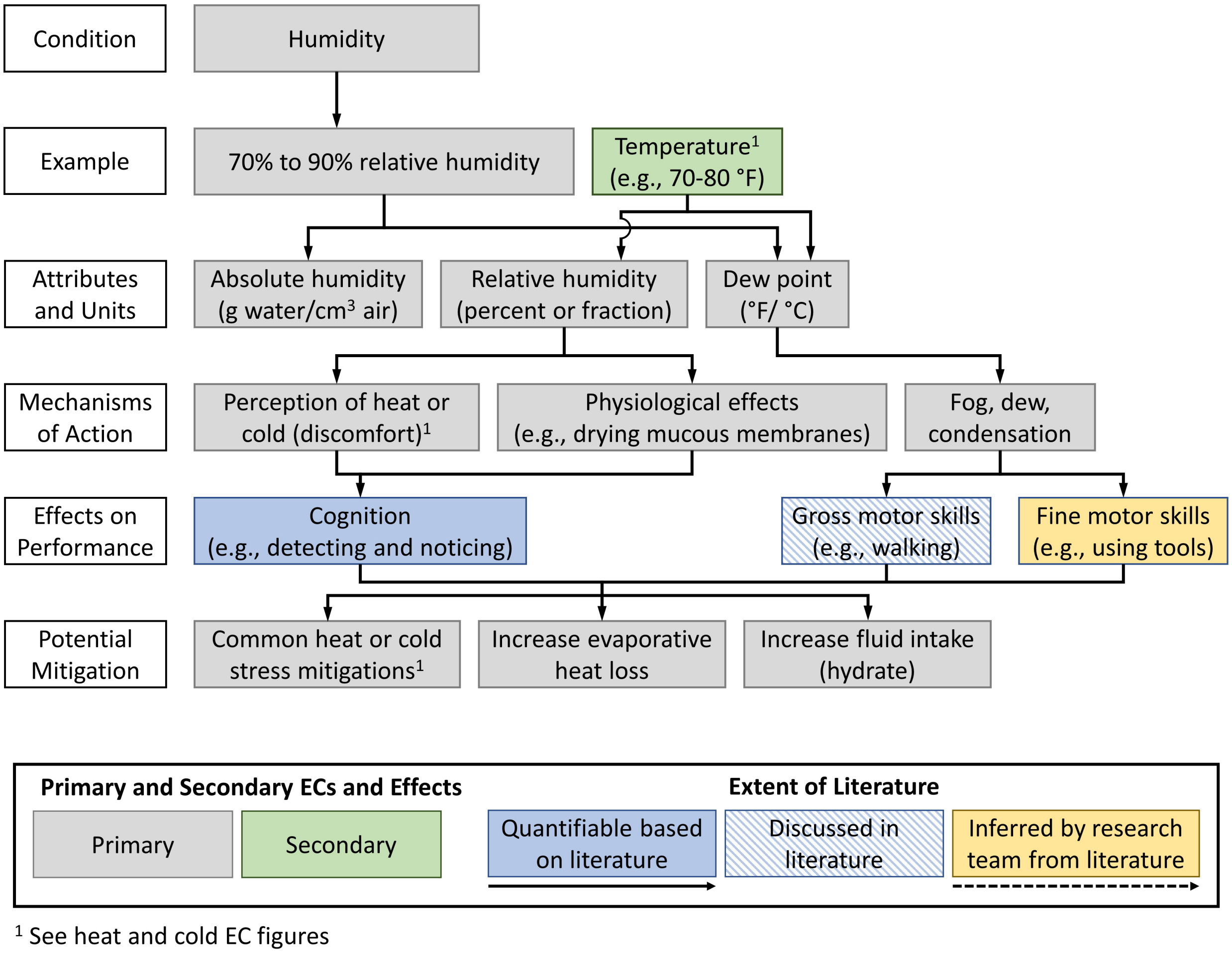

Figure 7.1 Humidity effects overview[4]

7.2 Attributes and Units of Measurement

Absolute humidity is the water content measured per volume of air at a given temperature. It is typically expressed in grams per cubic centimeter (g/cm³). A more commonly used measure of humidity is relative humidity, the ratio of the amount of water vapor in the air to the total amount of water vapor air can hold at a given temperature. The related dew point is the temperature (in °F or °C) at which water vapor in the air condenses into liquid water. Absolute humidity, relative humidity, and dew point can all be measured using common hydrometers. Clouds or fog can form when the relative humidity approaches 100 percent (i.e., when the ambient air temperature and dew point are the same).

Humidity, in combination with air temperature, wind, and radiant heat, is important to how heat and cold are experienced as stimuli by humans. This is why humidity is an integral part of the commonly used[5] heat and cold indices—WBGT, Heat Index, and Effective Temperature Index.

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[4] Only some performance demands are listed here as others may not be significant for the example condition.

[5] In their review of a dozen of the more common indices/measures, Blazejczyk et al. (2012) reported that >100 indices have been proposed over the last century, and perhaps ~40 are in use at the time of the study.

- WBGT (defined in Chapter 2, Heat) becomes a less reliable stress indicator when relative humidity is high and there is little air movement (Budd, 2008).
- The Heat Index is another measure that describes perceived temperature, used often in weather reporting. Heat Index combines temperature and relative humidity, but it doesn't take into account wind and sun or other radiative heating (Callejon-Ferre et al., 2011; NOAA-NWS, 2017).
- The Effective Temperature Index is a single figure index of the sensation heat or cold. Although developed primarily to address warmth and comfort, its range includes air temperatures >32 °F (0 °C). Consequently, it can also be used to address coldness and comfort (Blazejczyk et al., 2012; Missenard, 1933). The Effective Temperature Index combines air temperature, humidity, and wind velocity.

All three of these measures, as well as relative humidity, can be obtained using commonly available psychrometers. The WBGT, as a general measure of heat stress, tends to be preferred over the Effective Temperature Index for research purposes because the WBGT is designed for broader applications (i.e., not necessarily near the comfort zone and not based on a subjective scale using sedentary clothed subjects) (NUREG/CR-5680, Echeverria et al., 1994). However, the Effective Temperature Index has a predictive value regarding the affective perception of air temperature from cold to hot that is not provided by WBGT)[6]. NOAA/NWS (2014a) quantified combinations of temperature and relative humidity for which heat disorders are likely in terms of caution and danger zones (Table 7.1).

7.3 Time Variation of Humidity

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to severely elevated humidity. More importantly, because the humidity levels during a flood may change, personnel exposures to this EC may also be variable in time. In other words, the severity of elevated humidity is time dependent and may vary significantly over the duration of execution of a manual action or task.

Figure 7.2 illustrates the variation in relative humidity that might occur before, during, and after a flooding event. Local conditions may alter these broad levels. For example, a room or area experiencing radiant heat from a heater or cooling from a dehumidifier could have lower or higher humidity, respectively. Also portrayed in the figure are three MAs (MA 1, MA 2, and MA 3) being performed during the course of a flooding event, which may be affected by a mix of the localized and regional conditions. Statistical, probabilistic, and worst-case scenario analyses may be used for considerations of storm induced humidity and accompanying variations of co-occurring ECs.

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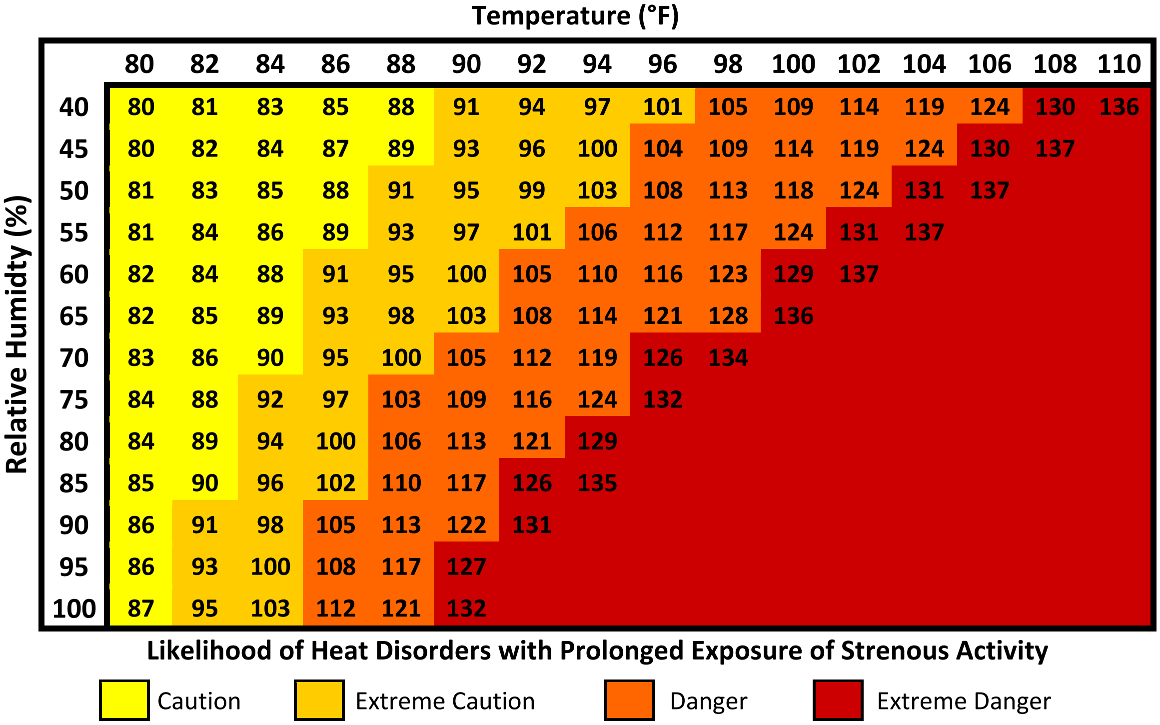
[6] The Universal Thermal Climate Index is among several thermal balance indices that incorporate humidity, air temperature, and other variables toward more accurately assessing the effect of heat and cold on discomfort and stress (Blazejczyk et al., 2012). The present review/report emphasizes the classical, more readily computed, indices because they have been employed in virtually all the previous effects literature.

7.4 Mechanisms of Action

The principal mechanism by which high humidity affects performance is by affecting perceptions, comfort, visibility, slipperiness[7], and well-being, particularly when ambient temperatures are either especially hot or cold. As discussed in more detail in Chapter 2, in hot weather, high humidity slows the evaporation of sweat (Masterton & Richardson, 1979), an important cooling mechanism for the body. Higher humidity is related to reduced heat tolerance, higher subjective discomfort, and performance decrements, especially for manual vs. sedentary tasks. As discussed in more detail in Chapter 3, in cold weather, high humidity enhances heat transfer away from the body. Low humidity can also cause discomfort, especially when accompanied by wind, by irritating eyes, drying skin and mucus membranes, and leading to dehydration from fluid loss during exhalation and sweating.

Table 7.1 Risk of heat disorders based on heat and humidity (NOAA-NWS, 2014a)



Temperature (°F)

Relative Humidty (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	131	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure of Strenous Activity

🟨 Caution 🟨 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Other mechanisms involve condensation of the moisture during conditions of high humidity. Fog may be produced when droplets of moisture in the air condense under these conditions (see Chapter 9, Precipitation). In addition, fog can be difficult to see through, thus impairing vision. Condensation of fog onto eyewear and other glass and plastic surfaces can reduce transparency and require frequent cleaning. It can make surfaces such as the pavement, the ground, and worker skin, clothing, and equipment, wet and slippery. These effects may be exacerbated, if air temperatures drop below 32 °F (0 °C) because fogged display and/or other

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[7] Slipperiness includes "conditions underfoot which may interfere with human beings, causing a foot slide that may result in injury or harmful loading of body tissues due to a sudden release of energy" (Grönqvist et al., 2001) and surfaces or objects that are difficult to hold firmly or stand on because they are smooth, wet, or slimy.

surfaces may become ice glazed with frozen surface moisture (see Chapter 11, Ice and Snowpack). Consequently, condensation related to high humidity may have a wide range of performance degradation effects (particularly when combined with other thermal factors).

7.5 Effects on Performance

Empirically examined effects of humidity alone (i.e., separate from temperature) as an EC affecting psychological and behavioral performance are rare, because most important effects of humidity are mediated through temperature. Effects have been shown on foot mobility, visual

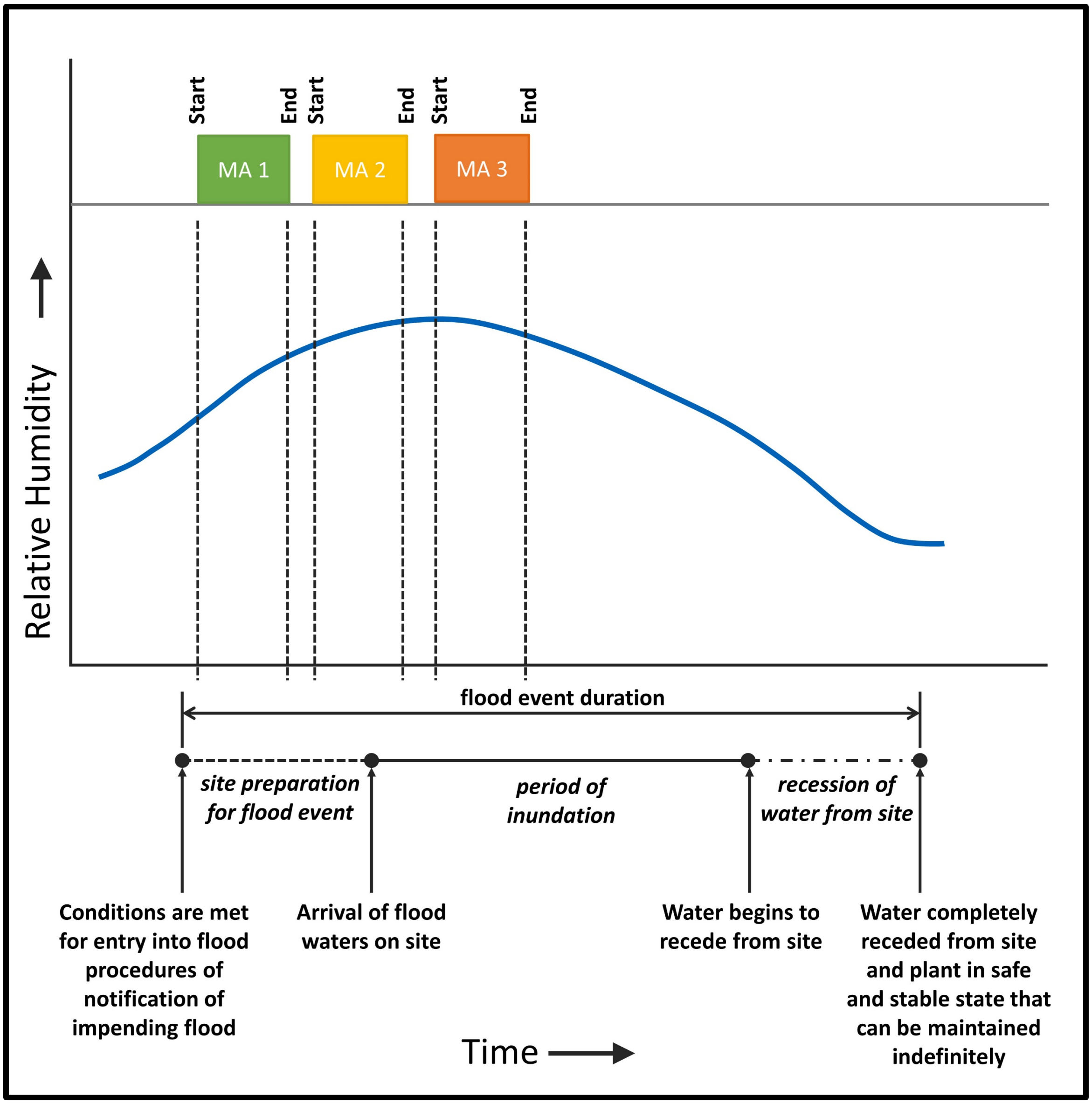


Figure 7.2 An illustration of humidity variation during an example of a hypothetical flooding event

recognition and discrimination, attention and judgment, as well as accident potential (e.g., Chang et al., 2016).

7.5.1 Gross Motor Skills: Foot Mobility

Several lines of field evidence show that high humidity slows walking speed (Chang et al., 2016; Richmond et al., 2015; Wilkinson et al., 1964). In this regard, Williamson et al. (1974) found that their sample population took 20 percent longer to complete a walking task during the tropical "wet season" (average of 83 °F (28 °C)) with 85 percent humidity during the workday) than it took during the "dry season" (average of 85 °F (29 °C) and 70 percent humidity). Adding support, Richmond et al. (2015) more recently reported effects of slick mud on walking energetics (and speed) associated with military studies. Finally, Chang et al (2016) noted the increased potential for slips and falls when surfaces are slippery, with a consequent tendency for individuals to walk slower in compensation. Collectively, these studies indicate that increased slipperiness associated with high humidity appears to affect walking speed and foot mobility.

7.5.2 Visual Recognition and Discrimination

When relative humidity approaches 100 percent, secondary ECs such as clouds and/or fog may become an issue. Both clouds and fog have the potential to affect activities requiring vision, especially those involving moving vehicles, although obscured vision may also hamper walking. With respect to operating vehicles, wet pavement associated with high humidity (whether it be the condensation of water droplets on pavement or humidity slowed drying of pavement after a rain) can increase the rate of accidents from loss of control (e.g., hydroplaning, wheel spinning, and braking inefficiency). Awareness of this risk causes careful drivers to reduce speed (Rossetti & Johnsen, 2011). Lowered visibility due to humidity caused fog may result in reduced speed, increased difficulty reading signage and following roads and pathways, as well as an increased risk of accidents. Although vehicle travel onsite is likely to involve relatively short distances and low speed limits, workers and materials arriving from offsite may involve longer and higher-speed vehicle travel.

7.5.3 Discomfort Distracted Attention and Judgment

Although unlikely to occur outdoors during flooding events, low relative humidity (<30 percent) has been associated with increased eye irritation, which may negatively affect work involving visual displays (Wolkoff & Kjærgaard, 2007). When relative humidity falls to 10 percent or below, mucous membranes in the nose and eyes become dry (Sunwoo et al., 2006), which increases the occurrence of nosebleeds. Particularly low humidity can speed evaporation to the point that mean skin temperature decreases, which can cause cold temperatures to both seem colder than they are and exacerbate the effects of cold temperatures (see Chapter 3, Cold). Conversely, continuous exposure to humid, hot environments can result in sleep difficulties with associated adverse effects on physical, perceptual, and cognitive performance (Steele et al., 1989). Sleep loss and related fatigue have been shown to be associated with poor judgment and increased accident rates (e.g., Colquhoun, 1971). Unless the preparation or mitigation activities extend over a period of several days, the effects of humidity on sleep are unlikely to represent an important consideration.

Subjective discomfort and performance effects associated with humidity may be best considered as part of environmental heat or cold. As with any other potentially distracting stimulus, discomfort due to humidity can consume attentional resources, resulting in performance decrements, especially for complex tasks (Chase et al., 2005). The degree to which humidity is uniquely responsible for attentional decrements cannot be determined from the available research literature (and arguably should be considered as an integral part of combination measures of temperature, wind, and humidity). Consequently, a portion of the attention allocation and division effects shown in the WBGT literature, especially when the researcher has controlled for individual differences in task abilities (e.g., Chase et al., 2005), may be attributable to the attention consuming nature of subjective discomfort, to which humidity is a contributor. Cognitive processes, e.g., memory and problem solving, consequently would almost certainly show humidity associated discomfort effects, because attentive processes are fundamental to their success.

7.5.4 Recommended Limits

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) recommends relative humidity levels between 30 and 70 percent to maintain comfort in work environments. Relative humidity above 70 percent can encourage the growth and spread of microbes and fungi (Baughman & Arens, 1996) and aggravate their tendency to promote disease. Relative humidity under 30 percent has been associated with increased eye irritation (Wolkoff & Kjærgaard, 2007). The mucous membranes in the nose and eyes become dry and mean skin temperature decreases when relative humidity is at or below 10 percent (Sunwoo et al., 2006).

7.6 Potential Mitigation Measures and Their Effectiveness

Measures to mitigate the adverse effects of humidity include modifying clothing and equipment to limit fogging and condensation, modifying footwear and equipment to increase grip and reduce slipping, and providing liquids for rehydration and cooling. Specifically,

- Provide nonslip footwear and gloves, which can increase grip and reduce slippage when walking or conducting hand work under high humidity conditions.
- Coat eyewear and displays with antifogging materials to reduce condensation and fogging.
- Increase air movement, through location and use of fans, to allow more efficient evaporative cooling.
- Provide misting in hot, low humidity conditions to enhance evaporative cooling and heat lamps to minimize heat loss in cold conditions.
- Provide plenty of cool/cold water, both for drinking and for rinsing and cooling the head and the body in hot conditions, and hot drinks in cold conditions.
- Allow heat adaptive work clothing that is unlikely to adhere to skin in hot, high humidity conditions (e.g., lightweight fabric shorts and shirts) and undergarments that wick moisture and provide warmth for cold, high humidity conditions.
- Consider using heat pumps or air conditioners, with humidifiers or dehumidifiers as appropriate, to moderate temperature and indoor air humidity in break rooms and rest areas to promote recovery and ameliorate sleep loss effects during multiday efforts.

7.7 Interactions of Humidity with Other Environmental Conditions

Humidity is an important factor in determining the subjective and objective performance effects of heat and cold. Humidity, especially high relative humidity, can produce the secondary ECs, fog, and clouds.

7.8 Summary of Research on Humidity Impacts

The state of the research literature addressing the effects of humidity on performance demands is summarized in Table 7.2.

Table 7.2 Humidity effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	2,4	(a)(c)
Sensation and visual recognition	3	(a)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	4	(a) (c)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	4	(a) (c)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	2	(a)
Gross motor skills – heavy and light	3	(b) (c)
Other neurophysiological functions	4	(c)
Teamwork		
Reading and writing	4	(a) (c)
Oral face-to-face and electronic communication	4	(c)
Cooperation, crew interaction, and command and control	3	(a) (c)

Assumptions and Limitations of Applicability

(a) When relative humidity approaches 100%, eyewear, displays, windshields and windows, may fog up, compromising visual activities, especially distance vision. This may add to the disruptive effects of fog itself (see Precipitation). At the same time, controls surfaces and tool handles surfaces may become slippery. Subsequent air temperature drops to freezing levels can also lead to problematical ice glazing of dampened surfaces.

(b) Some evidence demonstrates an association between humidity and foot mobility, but it cannot be disentangled from slipperiness, soil moisture (essentially increasing foot-friction), etc.

(c) Discomfort and humidity added challenges that may affect complex tasks (see Chapter 2, Heat, and Chapter 3, Cold, for discussions).

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) *No information (a gap).*

8 WIND

8.1 Introduction

Personnel may encounter wind during the execution of MAs before, during, and after a potential or anticipated NPP site flooding event. For example, wind may occur when a storm is approaching and may continue long after the flooding itself has passed. Wind has the potential to adversely affect the performance of MAs depending upon its direction (which may be fixed or changing) and speed (steady and/or with accompanying gusts). Wind-associated instability can impede movement, slow the execution of work, and even occasionally topple an individual. At the same time, wind directed at the eyes, which may produce tearing or send precipitation, dust, or sea spray into the eyes, may obscure the visibility of distant objects (if not the ground itself). Flying debris, which can present impact hazards, and sea spray, which can wet surfaces, can adversely affect safety and performance. To protect against such hazards, personnel working in windy conditions should wear appropriate protective gear (e.g., protective eyewear, hardhats, and/or dust masks). Noise associated with wind (and accompanying precipitation, when it occurs) may also disrupt communications and thereby affect teamwork (see Chapter 4, Noise). When coupled with cold or warm temperature, wind may have adverse effects on the performance of MAs, (e.g., gross and fine motor skills, complex problem-solving skills (see Chapter 2, Heat, and Chapter 3, Cold)). Figure 8.1 provides an overview of wind attributes and effects as well as their literature support levels and MA relevance.

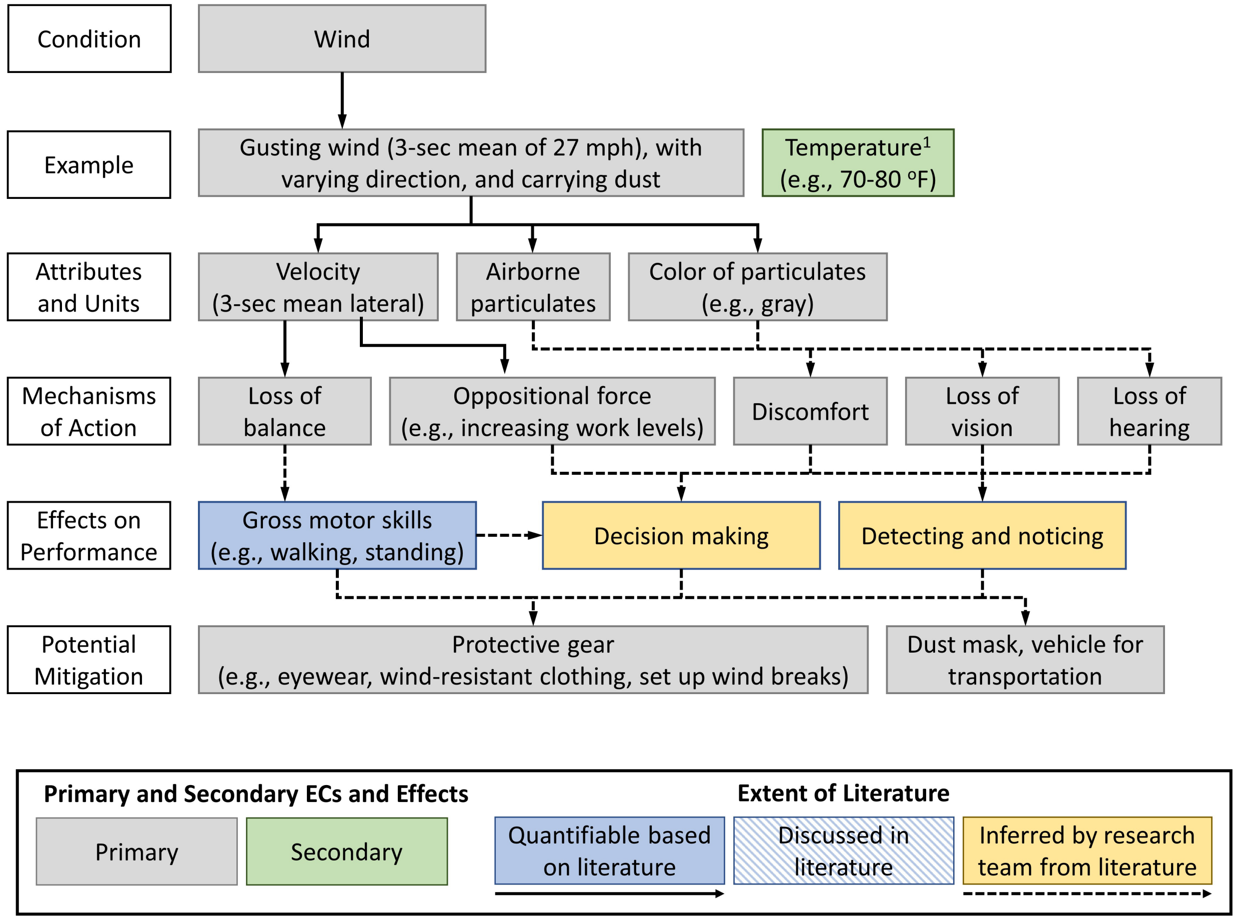
8.2 Attributes and Units

Quantitative effects on MAs have been studied for wind speed and direction. Wind speed, which is variable with gusts, is often considered in terms of its average over 3-s increments (U_3). This increment is considered because ~3 s is the increment over which the body effectively integrates and experiences the combined effects of wind gusts as suggested by Melbourne (1978) and standardized by Murakami and Deguchi (1981). Velocity is typically measured (m/s, km/s; or alternately ft/s and mph) by an anemometer, which also provides compass direction. Direction, however, is often unspecified, both in general guidelines and analyses of effects on performance. This is particularly true in research addressing either the broad environmental effects of wind and/or the potential for toppling (where wind direction and/or operator orientation are neither necessarily stationary and where a worst-case direction is generally assumed for guideline purposes).

8.3 Time Variation of Wind

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to high winds. As shown, because the wind velocity during a flood could dynamically change, personnel exposure to this EC is also variable in time. In other words, the severity of wind is time dependent and may vary significantly over the duration of execution of a manual action or task (e.g., see variations in hurricane wind velocities for MAs 2 and 3 in Figure 8.2). Although there could be a relatively “quiet” time during the eye of a hurricane passing over a site, working conditions may not be amenable due to presence of debris from the earlier passage of hurricane force winds and the impending increase in wind speeds and possible reversal of wind direction as the eyewall passes.

Smoothed (with gusts removed) trends in storm and hurricane wind velocities are exemplified in Figure 8.2 (not illustrated are accompanying directional complexities), for both typical storm



[1] See heat and cold EC figures

Figure 8.1 Wind effects overview[1]

winds and hurricane winds. The latter assumes a temporary hurricane eye related reduction in wind velocity.

8.4 Mechanisms of Action

Wind speed (especially 3 s averages) and direction are the primary attributes of wind for which there is literature describing predictable, quantitative MA effects[2]. Researchers have focused primarily on safety concerns, and the greatest research attention has been given to human instability, or loss of balance (as with standing and moving water, discussed in Chapter 10). While also pointing to the visual and other performance threats posed by debris, Stathopoulos (2009) has suggested that the Beaufort Scale for land areas, provides insight into the mechanical effects of wind of different speeds on the human body (see Table 8.1).

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[1] Only some performance demands are listed here, as others may not be significant for the example condition.

[2] Buildings and other objects, which can alter wind attributes, have also been studied with respect to city pedestrian activities. However, these studies have typically been focused more on modeling layout than human effects (e.g., Stathopoulos, 2009).

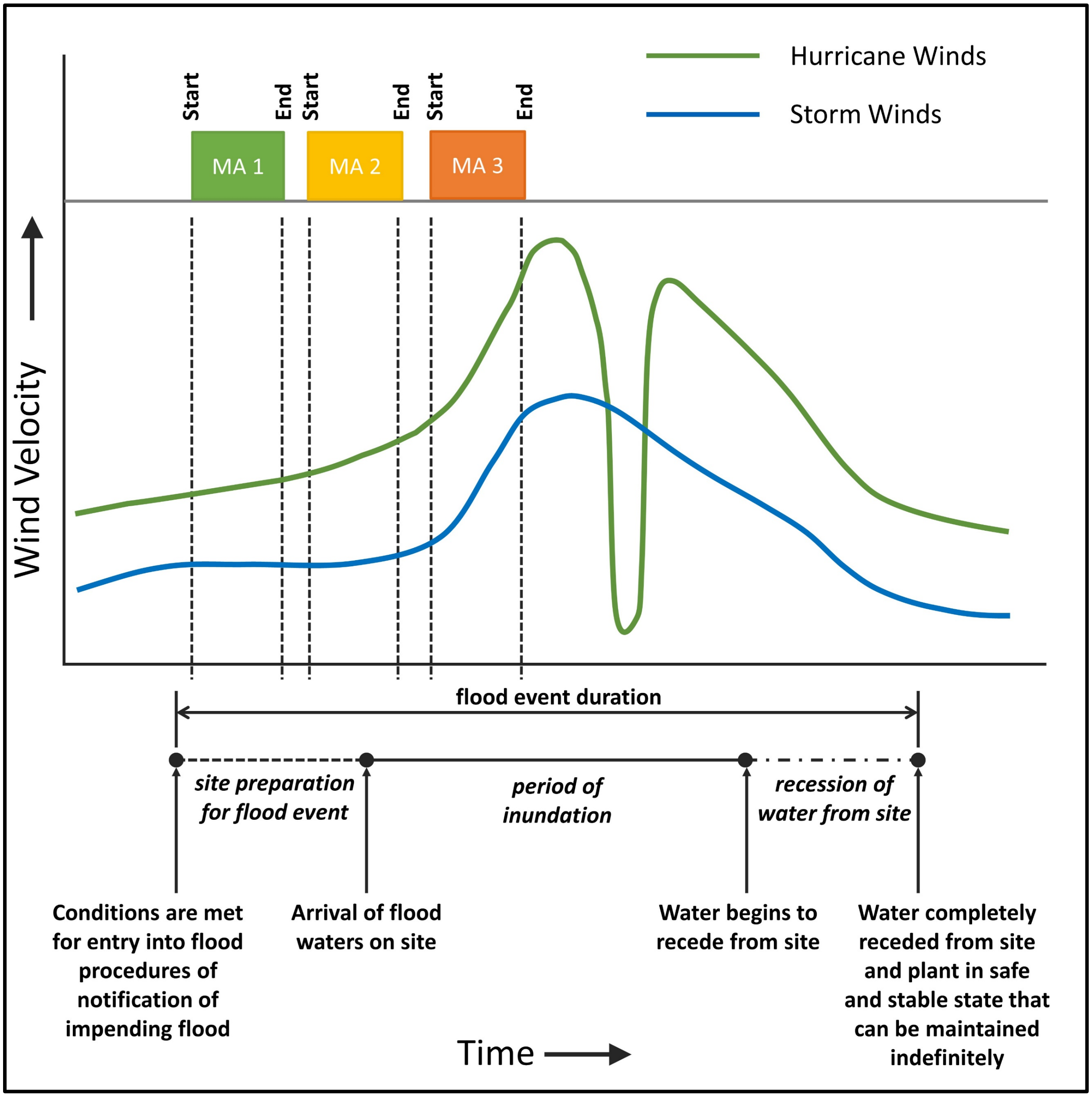

Figure 8.2 An illustration of wind variation during an example of a hypothetical flooding event

Aside from relative direction, the toppling effects of wind depend on mechanical moment instability variables. Walking personnel are less stable than standing personnel, who are less stable than sitting personnel. Lighter individuals are less stable than heavier ones. Loose clothing, with greater sail area, provides for less stability than form fitting clothing (e.g., Jordan et al., 2008).

Research on the effects of wind on performance have focused almost exclusively on its direct mechanical effects, which include those created by the impact of the force of the wind on gross

Table 8.1 Beaufort scale of wind as used on land and estimating speed

Beaufort Number	Descrip-tive Term	Speed (km/hr)	Speed (~mi/h)	Specification for Estimating Speed
0	Calm	< 2	< 2	Smoke rises vertically.
1	Light Air	2–5	2–3	Direction of wind shown by smoke drift but not by wind vanes.
2	Light Breeze	6–11	4–7	Wind felt on face; leaves rustle; ordinary vane moved by wind.
3	Gentle Breeze	12–19	7–12	Leaves and small twigs in constant motion; wind extends light flag.
4	Moderate Breeze	20–29	12–18	Raises dust and loose paper; small branches are moved.
5	Fresh Breeze	30–39	19–24	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong Breeze	40–50	25–31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Near Gale	51–61	32–38	Whole trees in motion; inconvenience felt in walking against the wind.
8	Gale	60–74	37–46	Breaks twigs off trees; generally impedes progress.
9	Strong Gale	75–87	47–54	Slight structural damage occurs e.g. to roofing shingles, TV antennae, etc.
10	Storm	88–102	55–63	Seldom experienced inland [except during tornadoes]; trees uprooted; considerable structural damage occurs.
11	Violent Storm	103–116	64–72	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	> 116	> 72	

Note: 10 km/h= 6.21 mi/h *Source: ASCE, 2004*

motor behavior. Beyond this there is some research on the acoustical physics describing how wind affects the acoustical environment and associated communication, both verbal and microphone (c.f. Wilson et al., 2007), but other effects (e.g., visibility) have yet to be have not been studied. However, as discussed for other ECs, Dovan (2013), Staal (2004), and Lupien et al (2007) have noted that while broadly enhancing gross flight-fight performances (e.g., strength), high arousal levels, such as those that would occur from exposure to high windspeeds, interfere with performance involving complex skills, fine muscle movements, coordination, steadiness, as well as general cognition. Research on other ECs that create perceptions of risk and cause discomfort indicates that high wind speed, particularly if accompanied by flying debris, would cause workload stress effects. These would be anticipated to adversely impact understanding, sensemaking, decision making, and teamwork. Presumably, as the physical effects of increasing wind speed are perceived, individuals begin to assess the risk of bodily harm. The resulting anxiety, distraction, and/or rumination would affect all of the more resource limited cognitive performance variables (e.g., detecting and noticing, understanding and noticing, as well as fine and gross motor skills).

8.5 Effects on Performance

Although the effects of wind on stability and the level of effort required while walking or standing have been widely studied, little information has been assembled about the associated effects of the physical force of wind on higher-level performance demands (e.g., fine motor skills, decision making, detecting and noticing, etc.). Similarly, the effects of wind caused discomfort and perceptions of risk on simple and complex cognition and communication and teamwork have received little research examination.

8.5.1 Toppling and Gross Motor Performance

As the 3 s averaged wind velocity "U_{3sec}" approaches a toppling threshold, human performance is affected much as with floodwaters (see Chapter 10, Standing and Moving Water). The effects of wind can include similar difficulties in walking, leaning over to lift objects, restricted range of motion, and limited dual-hand activities (the last arguably because of the need to hold onto stationary supports). At higher U_{3sec}, any gross motor performance (e.g., standing or walking) may be significantly affected, as the body approaches toppling. The forces leading to toppling increase the probability of injuries from falls.

8.5.2 Fine Motor Skills, Simple and Complex Cognition

Although research is lacking on wind's effects on the higher-level performance demands, by logical extension, it is reasonable to expect that they would be adversely affected when the more basic performance demands (e.g., standing and walking) become challenged by wind. These higher-order effects have not been formally addressed in the research literature.

Agdas et al. (2012) have shown that wind can generate perceptions of risk and associated fear and anxiety, especially when individuals do not have previous experience with the specific conditions. Likewise, Agdas et al. (2012) found that perceptions of risk influence participants' perception of wind speed. Although research specific to wind is lacking, stress and anxiety related mechanisms and the additional workload associated with perception of risk, especially in inexperienced personnel, could lead to decrements in detecting and noticing, understanding, and decision making in many other situations (see Bourne & Yaroush, 2003). Hancock and Desmond (2001) provided a review of perceptions of risk effects on cognition. Because anxiety related effects of wind on higher-level performance demands have not been examined quantitatively, they are a candidate for future research.

8.5.3 Recommended Limits

Table 8.2 provides a summary of proposed unsheltered performance limits that are applicable to walking, carrying, and other manual handling tasks and to proposed limits for vehicle travel when walking is wind limited[3].

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[3] Baker (2015) offers an alternative, but not time tested, risk based analysis approach to pedestrian and vehicle safety in windy environments.

Table 8.2 Outdoor worker and in-vehicle wind limits

UNSHELTERED PERFORMANCE LIMITS			
Murakami-Deguchi Limits for qualitatively evaluating (stability and perception of risk) wind effects on pedestrians where U (m/s) is the instantaneous wind speed average over 3 s			
		English Units	**Metric Units**
No Effect		$U \le 16.4$ ft/s	$U \le 5$ m/s
Some Effect		16.4 m/s > $U \le 32.8$ ft/s	5 m/s > $U \le 10$ m/s
Serious Effect		32.8 m/s > $U \le 49.2$ m/s	10 m/s > $U \le 15$ m/s
Very Serious Effect		$U > 49.2$ ft/s	$U > 15$ m/s
These may be recast to reflect a quadratic function with approximately a doubling (~2.25) of the proportional-increase (R) in time required for walking, carrying, and manual-handling (e.g., fine motor) at 7.5 m/s to an ~9-fold increase at 15 m/s			
		English Units	**Metric Units**
$R = 1$	for	$U \le 16.4$ ft/s	$U \le 5$ m/s
$R = (U/5)^{2,}$ U in m/s	for	$U > 16.4$ ft/s	$U > 5$ m/s
WITHIN VEHICLE LIMITS Rodriguez et al. (2014; 2015) explored high-wind vehicle control performance for cars, ambulances, and buses. This suggested that—neglecting debris—vehicle low speed movements would be possible during hurricane wind speeds (74–95 mph), but clearly impossible in high category storms.			

Example:

Problem: An operator has to walk 300 m (~110 yd) to fetch required equipment. Estimate effects for an average wind speed of 12 m/s (~27 mph) for an operator that normally walks at 1.34 m/s (~3 mph).

Solution: Using the equation in Table 8.3 , $R = (12/5)^2 = 5.76$. Thus, while it would ordinarily take (100 m/1.34 m/s) = 74.6 s (~1 min 15 s) to walk to the equipment, under the effects of a wind speed of 12 m/s, it would take (5.76*74.6 s) = ~ 430 s (7 min 10 s) for the same one-way transit.

8.6 Potential Mitigation Measures and Their Effectiveness

A variety of temporary windbreaks can serve to markedly reduce external effects; for example, hung tarps at lower velocities (e.g., <20 mph) and strategically positioned large vehicles at higher velocities (e.g., <60 mph). These measures may cut the wind speeds experienced by workers by factors of 2 or 3, depending on the arrangement of the windbreaks and the variability of wind direction. Vehicles, used in this latter context, may also serve as sheltered transport to/from work areas (albeit in higher winds personnel may find it difficult to safely exit). As with walking in water, walking sticks can provide support when standing and walking in marginal wind conditions, but tying up one hand/arm to provide this additional support also tends to limit task performance. Appropriate personal protective gear (e.g., eyewear, hardhats, dust masks, nonslip boots, and wind-rain resistant clothing and nonslip gloves) may also reduce impacts (depending on interactions of wind with precipitation, etc.). The best mitigation may be to plan to perform required tasks during low wind speed periods (e.g., under U = 5 m/s or ~11mph).

8.7 Interactions of Wind with Other Environmental Conditions

Wind interacts with cold (wind chill) and heat (WBGT, evaporation rate), noise (albeit ill-defined Wilson et al., 2007); standing and moving water (see Webster et al., 2013), and precipitation (e.g., visual effects), as well as the secondary EC, windborne debris/dust.

8.8 Summary of Research on Wind Impacts.

Table 8.3 summarizes the state of the research literature addressing the effects of wind on performance demands.

Table 8.3 Wind effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	4	(b)
Sensation and visual recognition	4	(b)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	4	(b)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	4	(b)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	4	(b)
Gross motor skills – heavy and light	1	(a) (b)
Other neurophysiological functions	4	(b)
Teamwork		
Reading and writing	4	(b)
Oral face-to-face and electronic communication	3	(b) (c)
Cooperation, crew interaction, and command and control	4	(b)

Assumptions and Limitations of Applicability

(a) Gross Motor failure resulting from toppling, e.g. Murakami-Deguchi Limits (1981).

(b) Downstream effects are possible on other motor, perceptual, and/or higher cognition performance, either resulting from complete gross motor failure (toppling), or directly, through perception of risk activation (e.g., Dovan, 2013; Lupien et al., 2007)

(c) Electronic communication is made difficult through wind effects on microphones.

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) *Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.* *(4)No information (a gap).*

9 PRECIPITATION

9.1 Introduction

Precipitation occurs when water vapor condenses and falls to the ground as rain, sleet, hail, or snow. For the purposes of this review, only falling precipitation in its many forms is considered[1]. Once it reaches the ground, precipitation poses challenges addressed in other sections in this volume (i.e., standing and moving water, discussed in Chapter 10 and ice and snowpack discussed in Chapter 11). Precipitation in the form of rain is widespread throughout the United States, whereas snow is only common in northern latitude states or at higher elevations. Sleet and ice pellets are typically the result of snow melting as it falls through a warm atmospheric layer, then refreezing as it falls through sub-freezing air. Hail is associated with thunderstorms, which tend to be most common in the warmer, wetter areas of the United States (e.g., Southeast and the Midwest). The most immediate effects on performance of precipitation are related to its interference with visual perception of the environment, which is by far the most studied aspect of precipitation effects. Figure 9.1 presents the attributes of precipitation as well as their literature support levels and MA relevance.

9.2 Attributes and Units of Measurement

Precipitation is a form of liquid, solid, or transitional water falling under the force of gravity (AMS, 2012). Precipitation is typically measured in amount falling per time period (e.g., millimeters per hour [mm/h]) using standard rain gauges, which are cylinders with graduations present to allow depth measurement. Rates are assessed from depth differences over the time intervals of interest. Precipitation can also be measured with specialized and/or automated weight gauges, tipping bucket gages or pluviometers. For solid precipitation, readings are taken either before melting (via a snow gauge to determine the depth of solid precipitation that is falling or has fallen) or after melting (via a rain gauge after antifreeze has been added or melting has occurred after the device is brought indoors). Snow gauges are cone shaped devices that capture the snow, the depth of which can then be measured (and contents subsequently melted to determine the amount of water content). Snow pillows, which are about 4 feet square boxes of stainless steel or synthetic rubber containing an antifreeze solution, are used to collect snow as part of an automated system that measures the weight of the collected snow. Both rain and snow gauges can become inaccurate in windy conditions that variously cause precipitation to be (1) blown across the device opening rather than falling in, thus causing underreporting, or (2) blown into the opening, thus causing overreporting. Professional devices have evolved and now typically have protection against wind or splash.

9.3 Time Variation of Precipitation

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to intense precipitation. More importantly, because the precipitation intensity during a flood may change, personnel exposures to this EC may also be variable in time. In other words, the severity of precipitation is time dependent and may vary significantly over the duration of execution of a manual action or task.

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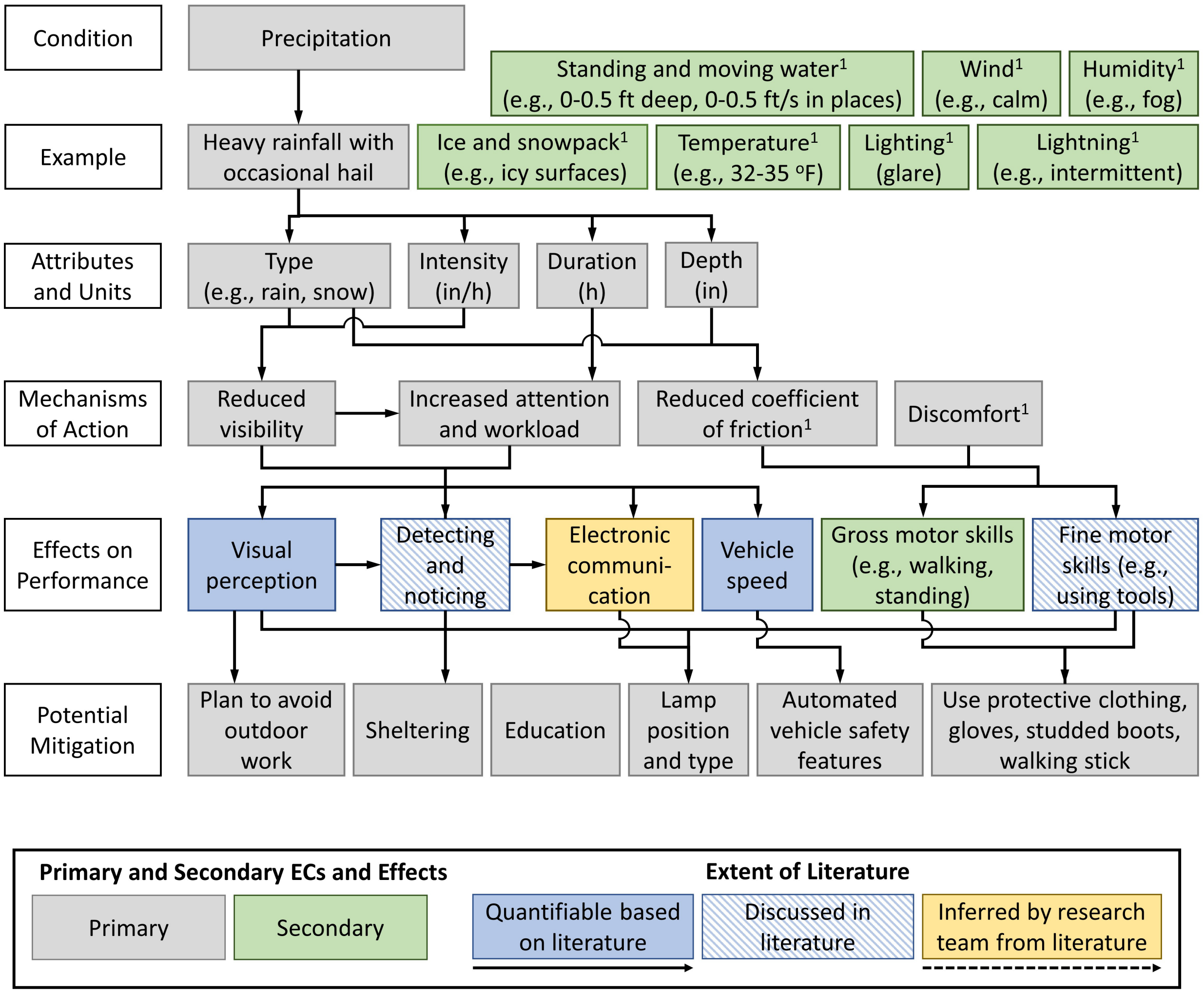
[1] There are technical distinctions between various forms of liquid and solid precipitation (AMS, 2012). Liquid forms, for example, include drizzle (also known as mist) and rain. Frozen forms of precipitation include snow (ice crystals throughout the life cycle), ice needles (frozen fog), ice pellets (small hail), hail, sleet, and graupel (slushy precipitation formed when freezing rain contacts snowflakes).



[1] See ice and snowpack, cold, lighting, wind, lightning, standing and moving water, and humidity EC figures

Figure 9.1 Precipitation effects overview[2]

Figure 9.2 illustrates the possible complexity of precipitation variations during a flooding event, with a local hail storm punctuating a period during a basin-wide storm. In this illustration, MAs (MA 1, MA 2, and MA 3) are portrayed as occurring sequentially with varied precipitation mixes complicating their timely completion. During a prospective or ongoing flooding event, weather reports may more or less accurately anticipate disruptive, near term variations in a basin-wide storm, but are less likely to anticipate the potential of local hail storms. Statistical, probabilistic, and worst-case considerations consequently are likely to be particularly important during analyses of prospective future flooding events where precipitation may be an issue.

9.3.1 Reduced Visibility

A common mechanism of action across all forms of precipitation is reduced visibility, which affects both workers on foot and workers in vehicles. The effective intensity of precipitation is

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[2] Only some performance demands are listed here, as others may not be significant for the example condition.

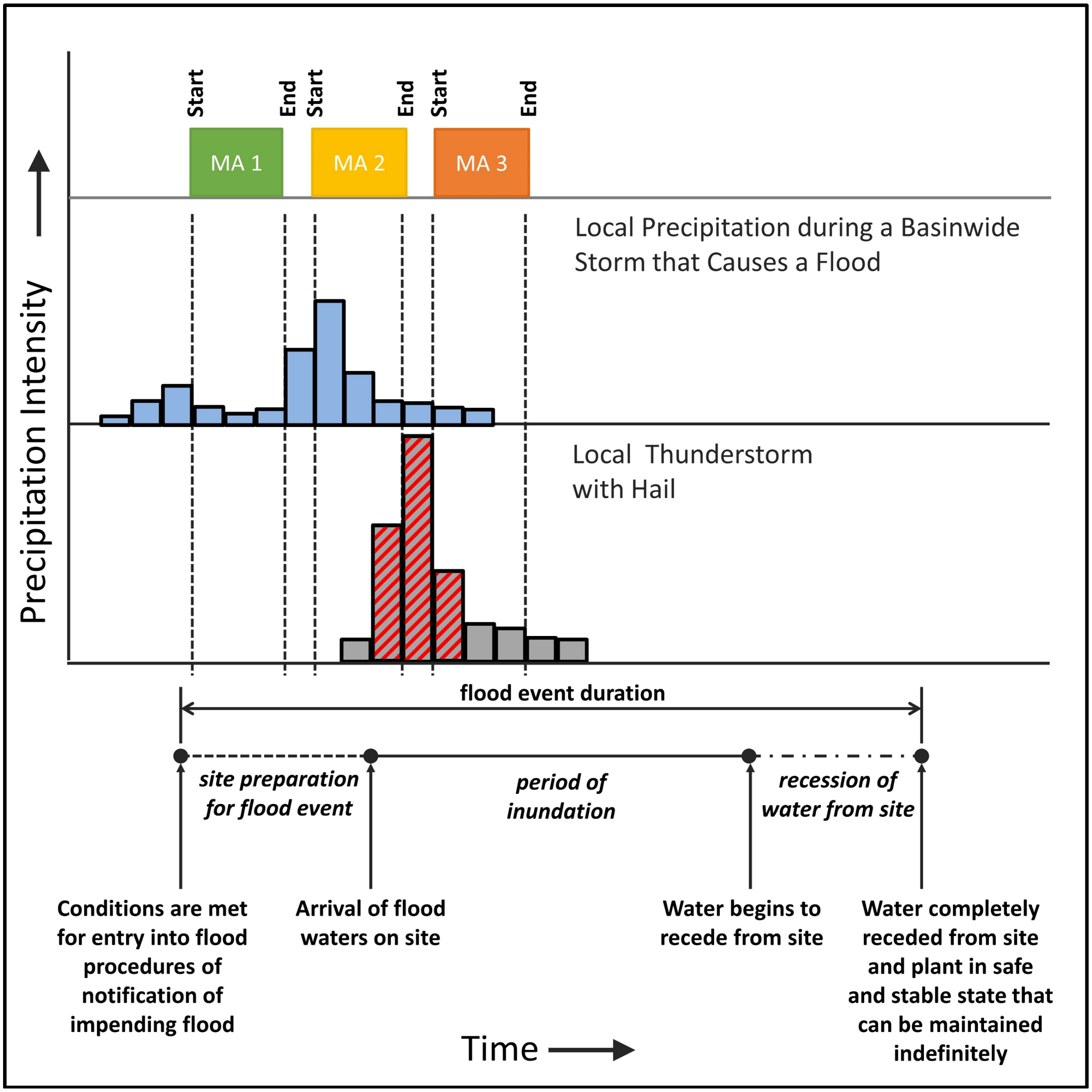

Figure 9.2 An illustration of hurricane and precipitation variation during an example of a hypothetical flooding event

increased as foot or vehicle speed increases. Movement speed increases the accumulation of precipitation on windscreens or eyewear, which may overwhelm wiper clearance in vehicles and require repeated eyewear cleaning by workers on foot.

9.3.2 Flooding Event

The preponderance of research on precipitation is focused on its effects on vehicle safety and travel at higher speed than would normally occur on NPP sites. This research points to a positive association between precipitation and automobile accident rates (Bertness, 1980;

Brodsky & Hakkert, 1988; Fridstrøm et al., 1995). However, there is a tendency for reductions in rates, if not absolute numbers, of associated fatalities (Brown & Baass, 1997; Eisenberg & Warner, 2005). This is attributed to the tendency of drivers to reduce their speeds and risky behaviors under storm conditions (e.g., rain or snow), but not enough to avoid an increase in low impact or minor accidents (Hooper et al., 2014). There may be a parallel for outdoor workers who are on foot (e.g., increased falls while walking), albeit while walking slower in precipitation (when long exposed with infrequent opportunities for sheltering).[3]

Precipitation may increase the potential for accidents by reducing visibility through either attenuation or reflection of light, in addition to visibility reductions created by direct moisture on eyewear, windows, and windshields and obstruction of the field of vision. In this regard, rain and snow can be thought of as random spatial variations in scene complexity (Nayar & Narasimhan, 1999)[4]. The greater this complexity is, and the farther light reflected from an object in the environment must travel through it, the greater difficulty the individual will have seeing those objects (e.g., road markers, signs, other individuals or vehicles, obstacles). Therefore, work that relies on distance vision outdoors (e.g., surveying, monitoring outdoor security cameras) may be rendered difficult or inaccurate due to the light attenuation effects of precipitation (Mason, 1978; Nayar & Narasimhan, 1999; H. W. O'Brien, 1970). Alternatively, when snowflakes are lit from the point of view of the observer, as in night driving with the lights on or standing with a flashlight pointing ahead, the white flakes can also reflect a great deal of light back toward the observer. This reflection from falling precipitation is termed glare (see Chapter 6, Light). Glare may adversely affect outdoor worker task performance. The glare created by headlights (versus a flashlight) interacting with snowfall presents a special problem for vehicles (e.g., snowplow operations where it has been associated with the failure to see the road or approaching obstacles and many accidents have occurred (Muthumani et al., 2015).

9.3.3 Increased Workload

Many studies suggest precipitation related accidents may be partly due to increased workload. Compared to driving on clear days or in darkness, simulator studies indicate that when driving in heavy rain, drivers check their mirrors less frequently and fixate (or visually dwell on an area of the visual field, as measured by an eye tracker) less frequently, but for longer periods. These workload related effects were observed even after complete removal of road slipperiness and associated simulator crash risk (Konstantopoulos et al., 2010). Similar studies in naturalistic environments also indicate that navigating through precipitation consumes processing resources. Researchers have observed an increase in traffic violations when it is raining (Zhang et al., 2013). These results suggest that individuals may have difficulty allocating their attention to the complex tasks of navigation and vehicle operation when precipitation is present. Because new objects attract attention (Yantis & Hillstrom, 1994), the shortened line of sight and greater effort required to see, identify, and geophysically locate features of the environment may increase drivers' difficulty in keeping their attention focused on the task and attending to signage and lane maintenance. Although not directly studied, it seems likely that increases in workload, including those created by the need to cope with the effects of the other mechanisms of action discussed below, account for some of the precipitation associated speed, quality, and safety issues also seen in workers on foot.

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[3] Outdoor workers are trained to walk slower over less well-defined surfaces with infrequent sheltering, but may rush to reduce time exposed to rain or to get to nearby shelter

[4] Random spatial variations in scene complexity are commonly referred to as "visual noise."

9.3.4 Induced Motion

Precipitation may also increase accidents as a consequence of induced motion effects that result when wind blows the flakes or droplets across the direction of travel. Induced motion is the tendency to perceive oneself as moving when one is not. This perception is often due to the motion of other items in the environment[5], Directional precipitation, especially snowfall, can produce this induced motion effect and systematic heading judgment errors in driving simulators (Richman et al., 2000; Royden & Hildreth, 1996; Warren & Saunders, 1995). These induced directional errors lead individuals to steer away from the path indicated by visible lane markings (Dyre & Lew, 2005; Lew et al., 2006). These inaccuracies in perception of motion can result in accidents both in vehicles as well as, arguably, for workers on foot. Awareness of this effect may lead to reduced movement speeds.

9.3.5 Slipperiness

Slipperiness created by already fallen precipitation may cause accidents for workers both on foot and in vehicles. Slipperiness, a reduction in the coefficient of friction, may occur on sidewalks, roads, and tools (e.g., see Chapter 10, Standing and Moving Water, and Chapter 11, Ice and Snowpack). On walkways, slipperiness can lead to an increase in slips and falls, and it can also markedly affect a pedestrian’s gait and speed (Richmond et al., 2015)[6]. On roads, this can lead to an increase in accidents, but can also reduce driver speed and automobile maneuverability, which, on public roads, can reduce roadway throughput and increase delays (FHWA, 2004), while in NPPs, may increase travel time and task length. On tools, slipperiness can lead to injuries involving tool slippage, but can also slow tasks performed with the tool. This phenomenon, and its ameliorations, are addressed in more detail in Chapter 10, Standing and Moving Water, and Chapter 11, Ice and Snowpack.

Slipperiness due to precipitation does not fully explain the complex association of precipitation with accidents. For example, Andrey and Yagar (1993) note that the risk of accidents returns to normal after rain stops, even though the road remains wet. Providing further evidence that slipperiness is not the only factor affecting accidents, some authors have shown that more accidents occur as the interval between precipitation events lengthens. For example, the number of accidents on a given rain/snow day is higher if 30 days have elapsed since the last precipitation event in comparison to an interval of only 2 days. Eisenberg (2004) posits two possible mechanisms for this lag effect; one physical and one behavioral. The physical mechanism involves the slipperiness resulting from the buildup of petroleum products on roads (e.g., oil, gasoline). Precipitation tends to wash these products from the road. With an interval of only 2 days between precipitation events, petroleum products will not have had an opportunity to build up. Much more can build up with an interval of over 30 days. When rains occur, the amount of petroleum products present to mix with the water will determine the overall reduction in the coefficient of friction that occurs (i.e., more time, more petroleum products, less friction). The behavioral explanation of lag effects is that as a result of their recent experience with rainy or snowy conditions, individuals are more cautious the next time these conditions occur. Recent experience conditions drivers to be more careful the next time it rains, but this association

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[5] A relatable example of induced motion is the seeming need to brake to arrest your vehicle’s backward progress (though it is stopped) in reaction to the car next to you inching forward.

[6] Richmond et al. (2015) provide an integrated review of past models predicting the energy costs of load carriage and walking (over a range of slope and variations in surfaces [surface characteristics]). Walking speeds, across the range of these conditions, may be estimated by assuming that a base energy expenditure will be maintained (i.e., relative to walking in ideal conditions ~2.5 mph.)

weakens as time passes. A parallel with this latter behavioral response has been informally suggested as holding for workers on foot (but again remains untested).

9.3.6 Discomfort

While drivers appear to reduce risky behaviors when precipitation occurs, for pedestrians, risk-taking behavior appears to increase. This is presumably because the discomfort associated with being exposed to precipitation motivates people to get out of the precipitation as soon as possible. For example, pedestrians show increased risk-taking behavior as evidenced by crossing against Don't Walk signals when rain or snow is present (Li & Fernie, 2010). The effort to reduce exposure to uncomfortable conditions may increase the likelihood that outdoor work will be rushed, extended safety protocols cut short, and inspections more cursory. This tendency to rush and give short shrift to safety procedures may result in an increase in accidents. At the same time, precipitation, or at least the weather characteristics associated with precipitation (e.g., cloudiness, wind), also appears to have a negative effect on mood and well-being (Connolly, 2013; Denissen et al., 2008), which may have a negative mediator relationship with worker productivity (Barnston, 1988).

The thermoregulatory effects of precipitation in cold weather are not dissimilar to those of being immersed in cold water (see Chapter 3, Cold, for further information). Nonetheless, Castellani et al. (2001) found in their study of cold stress that the effects of constant exercise in cold rain had a less intense effect on body temperature, subjective cold strain, and heart rate than did immersion in water of similar temperature. This reduced effect of rain as opposed to complete immersion may be related to the fact that heat retaining qualities of clothing are almost completely lost when one is immersed in water. This is because more of the skin surface area is exposed directly to cold water. Conversely, even when clothing is completely soaked in a rain situation, there are still parts of the skin surface that are not in direct and complete contact with water. However, participants in the Castellani et al. (2001) study were passive when submerged, i.e., not employing isometric or other exercise to generate body heat (as were participants in some other studies, e.g., Kaufman et al. (1988). Thus, the effect on temperature and subjective strain is lower from precipitation exposure than submersion in water of the same temperature (excluding the effect of wind, which would further increase the cooling effect of precipitation).

9.3.7 Perceptions of Risk

Perceptions of risk, especially the risk of falling and injury, have been shown to be an important psychological factor affecting performance, especially for workers less experienced with the threatening condition. Somewhat remarkably, research on the effects of severe weather conditions (precipitation, standing and moving water, ice and snowpack), though commonly addressing the effects of a reduced coefficient of friction (and hence slipperiness), has generally not studied perceptions of risk. In contrast, Webster et al. (2013) showed that moving water (also with reduced coefficient of friction and increased risk of falling) can generate perceptions of risk with associated fear and anxiety, especially for inexperienced workers. Anxiety or fear has the potential to produce additional effects on cognition, based on well-established stress and anxiety mechanisms (see Hancock & Desmond, 2001)[7]. The additional workload and neurochemical effects associated with perceptions of risk arguably are mechanisms jointly

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[7] The neurochemistry and adverse cognitive effects of water associated perceptions of risk may be anticipated to parallel those of activation as experimentally explored with regard to thermal and other stressors (e.g., Section 6.2, Heat, and Section 6.3, Cold).

leading to the decrements in detecting and noticing and understanding and decisionmaking associated with working in ECs that are painful or present the potential for injury (Bourne & Yaroush, 2003; Lupien et al., 2007).

9.4 Effects on Performance

One of the clearest effects of precipitation on performance is on completion time for outdoor work. Many outdoor jobs are either difficult to complete or otherwise produce unacceptable levels of risk of injury when performed in rain or when the ground is wet or saturated. Many construction and electrical jobs fall into this category. Work planners often consider local seasonal precipitation patterns when planning outdoor work that spans days or weeks, accounting for individual precipitation days and necessary drying periods in establishing the work schedule. McQuigg and Decker (1962), for example, attempted to quantify the effects of precipitation on work completion time to produce better planning estimates for outdoor tasks.

9.4.1 Reduced Gross Motor Speed and Greater Caution

As addressed earlier, reduced visibility, increased workload, and induced motion effects due to precipitation increase automobile accident rates despite drivers' compensatory behaviors that include slowing the vehicle, making slower and more gradual lane changes, and increasing following distances (FHWA, 2004). A primary effect is to reduce free flow speed (driver desired speed at low volume with no traffic control devices) and therefore increase travel time. The Federal Highway Administration (FHWA, 2004) points out that many of the quantitative influences of precipitation and other ECs cannot be disentangled from one another in naturalistic studies of traffic behavior to attribute any particular effect to one environmental cause. Pedestrians do not follow the compensatory behavior of drivers. As noted above, pedestrians engage in more risky behaviors while rushing to complete tasks.

Hranac et al. (2006) of the FHWA have modeled the effects of rain and snow on free flow vehicle speeds, as shown in Figure 9.3 and Figure 9.4. Figure 9.3 shows an approximately 1 percent reduction in free flow speed for every additional roughly 0.4 cm (4 mm) of rain per h (e.g., the difference between the orange 96.5 percent of normal free flow speed line and the cyan 95.5 percent line equates to an increase of about 0.4 cm per h of rain/snow). The individual lines remain approximately the same distance apart, thus the effects on free flow speed appear to be more or less linear, at least within the precipitation rates studied. The fact that free flow traffic speed effects in Figure 9.3 remain completely vertical shows that their model does not indicate any effects of visibility in rain. However, visibility was not measured from the point of view of a driver in a vehicle, so this likely neglects local effects of visibility. The graph shows an approximately 1 percent reduction in free flow speed for every additional roughly 0.4 cm (4 mm) of rain per h.

With respect to snow, visibility does show an influence in the Hranac et al. (2006) model, as shown in Figure 9.4. For example, snowfall of 0.1 cm (1 mm) per h produces a 6 percent reduction in free flow speed when visibility is over 4 km (red [94%] line), but a 16 percent reduction in free flow speed when visibility is reduced to near 1 km (blue [84%] line).

9.4.2 Attention/Workload

Precipitation has both direct and indirect impacts on attention and workload, which has implications for dual and multitasking behaviors such as those required while operating avehicle. If attentional resources or workload are significantly affected by snow, any additional

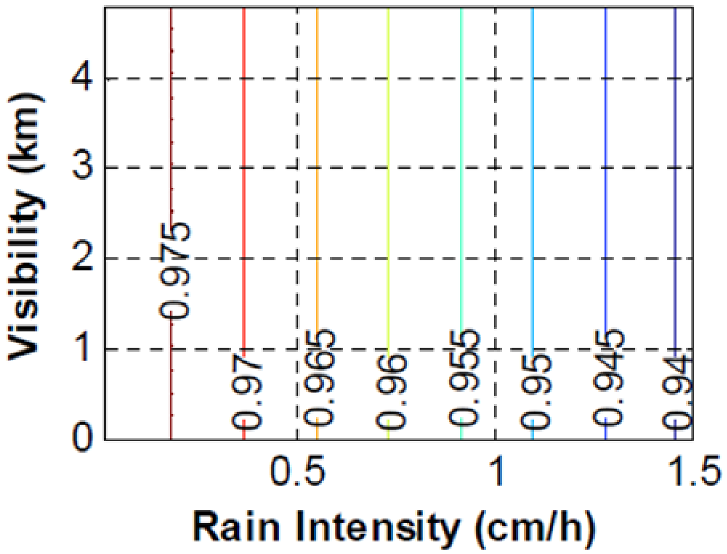

Figure 9.3 Free-flow wheeled vehicle speed reduction under rain conditions as a ratio to regular speed (Hranac et al., 2006)

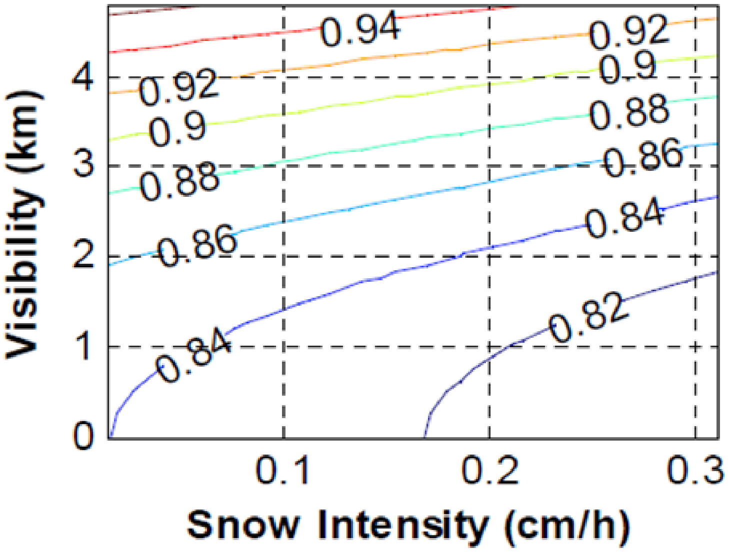

Figure 9.4 Free-flow wheeled vehicle speed reduction under snow conditions as a ratio to regular speed (Hranac et al., 2006)

task undertaken while driving or operating heavy machinery could result in errors (e.g., failures in lane maintenance become more common) and decrease the effective time available to react to unexpected events, resulting in the observed increase in accidents. For example, if a driver is attempting to navigate a new route, communicate over a radio, and perform other actions demanding attention, the task, the subject's driving performance, or both could be negatively affected. Tasks requiring focused attention (e.g., a maintenance worker on foot making a complex, essential repair), may be similarly affected by additional simultaneous demands (e.g., responding to an incoming communications).

When workers do not wear appropriately warm and water repellant clothing in precipitation and cold temperatures, they are likely to encounter performance effects outlined in Chapter 3, Cold; namely adverse impacts on motor skills, detecting and noticing, and decisionmaking (see Chapter 3, Cold, for a more detailed discussion of these effects). Lacking appropriate head gear and water-resistant clothing, workers may experience unnecessary levels of water-soaked discomfort, which will be more severe if the precipitation is freezing rain. Lack of nonslip gloves and/or footwear may likewise increase workload, perhaps exacerbated by the need to deal with slipperiness and accompanied by perception of risk. Fernando et al. (2013) demonstrated increases in both the time taken to complete and errors committed in a simple arithmetic operations task when completed outdoors in cold, rainy conditions. However, there is no way to disentangle the effects of the cold from that of the rain itself (e.g., rain noise, effects on vision), and the authors held that their result compared well with cold water immersion studies.

9.5 Potential Mitigation Measures and Their Effectiveness

Outdoor work can sometimes be postponed and/or staged to avoid working in precipitation, but when this is not possible, steps can be taken to improve the speed, quality, and safety of the work. Clothing that is sufficiently warm, given the time of year, can reduce discomfort effects, and a windproof, breathable waterproof, outer layer can reduce coldness, wetness, and discomfort. Temporary precipitation barriers (even a tarp) can reduce the effects of precipitation on visibility that are due to accumulation on eyewear and the obscuring of objects and on discomfort that is due to wetness. Reminding and encouraging workers to exercise special caution when working in precipitation by double checking work products, following safety procedures, wearing appropriate and reflective clothing, and reducing speed when driving or operating heavy machinery.[8] have been found to moderate the effects of precipitation on accident rates (e.g., Rossetti & Johnsen, 2011). Enhanced communication to provide coordination and information to workers and methods to enhance personnel and equipment visibility can help vehicle operators and workers maintain situational awareness.

The tendency for increased accident rates during precipitation may be mitigated somewhat by educating workers about the increased risk involved when precipitation is present. For workers operating vehicles, adoption of technological advances such as lane maintenance devices, perimeter cameras, and automatic collision avoidance devices will likely improve safety. As these emerging measures migrate to heavy equipment (e.g., pedestrian avoidance devices), safety with these machines should also improve. Similarly, preparing workers for outside work on foot with the following measures can serve to reduce the effects of precipitation: (1) temporary weather shelters (e.g., tarps and half-tents), wearing warm wind resistant and breathable water repellant clothing, along with (2) education of workers regarding the increased risk of accidents due to precipitation induced discomfort. Obviously, postponing work during precipitation would remove the risk completely, but this is often not feasible.

New technologies associated with wireless communication may also provide answers for vehicle related attentional resource and workload challenges caused by precipitation. The SAfety VEhicle Using Adaptive Interface Technology (SAVE-IT) Program, sponsored by the National Highway Traffic Safety Administration, is meant to algorithmically analyze real-time conditions while driving, and suppress aspects of in-vehicle interfaces (e.g., hands-free phone

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[8] This has been found to be effective in moderating the effects of precipitation on accident rates (e.g., Rossetti & Johnsen, 2011).

functionality) to limit the amount of information simultaneously sent to the driver (Brown et al., 2007). For example, if communication with team members is not pertinent to completion of the task, when someone is driving in precipitation, phone calls could be automatically routed to voice mail. The SAVE-IT Program and others like it have demonstrated the feasibility of this approach.

The reduced visibility and induced motion effects caused by the glare from snow can lead to accidents. Approaches to mitigating the glare effects of falling snow involve changing the type and positioning of headlights - narrow rather than wide beams; directed away from rather in the driver's line of sight (Muthumani et al., 2015) and changing their color (yellow tend to be subjectively less glare inducing (Bullough & Rea, 2011).[9]. Radar and other advanced vision display devices are rapidly becoming available to help drivers navigate through precipitation. These include lane maintenance devices, perimeter cameras, as well as pedestrian and automatic collision avoidance systems.

9.6 Interactions of Precipitation with Other Environmental Conditions

Precipitation often co-occurs with many other ECs including standing and moving water (in the form of flooding), ice and snowpack, cold, lightning, lighting (in the form of glare from falling snow), and wind. It can also co-occur with heat, noise, lighting, and humidity.

9.7 Summary of Research on Precipitation Impacts

The current state of research addressing the effects of precipitation on performance demands is summarized in Table 9.1.

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[9] It is not clear that yellow lights make an objective difference in glare

Table 9.1 Precipitation effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(b)
Sensation and visual recognition	2	(b)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	3	(b)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(b)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	2	(b)(c)
Gross motor skills – heavy and light	2	(a) (b)
Other neurophysiological functions	3	(b)
Teamwork		
Reading and writing	2	(b)
Oral face-to-face and electronic communication	4	(b)
Cooperation, crew interaction, and command and control	4	(b)

Assumptions and Limitations of Applicability

(a) Quantification of the effects of precipitation on time to complete work is used in construction/road work planning (e.g., McQuigg & Decker, 1962). To the extent these are largely gross motor tasks, one might expect similar effects on MAs involving similar work.

(b) Precipitation reduces visual perception, increasing associated processing workload and errors, thereby drawing resources away from concurrent and downstream action or cognitive activity that requires it.

(c) At least for the discrete and continuous fine motor tasks involved in driving, the effects on driving speed are well understood at the macro-level (see Figure 9.3 and Figure 9.4).

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) *No information (a gap).*

10 STANDING AND MOVING WATER

10.1 Introduction

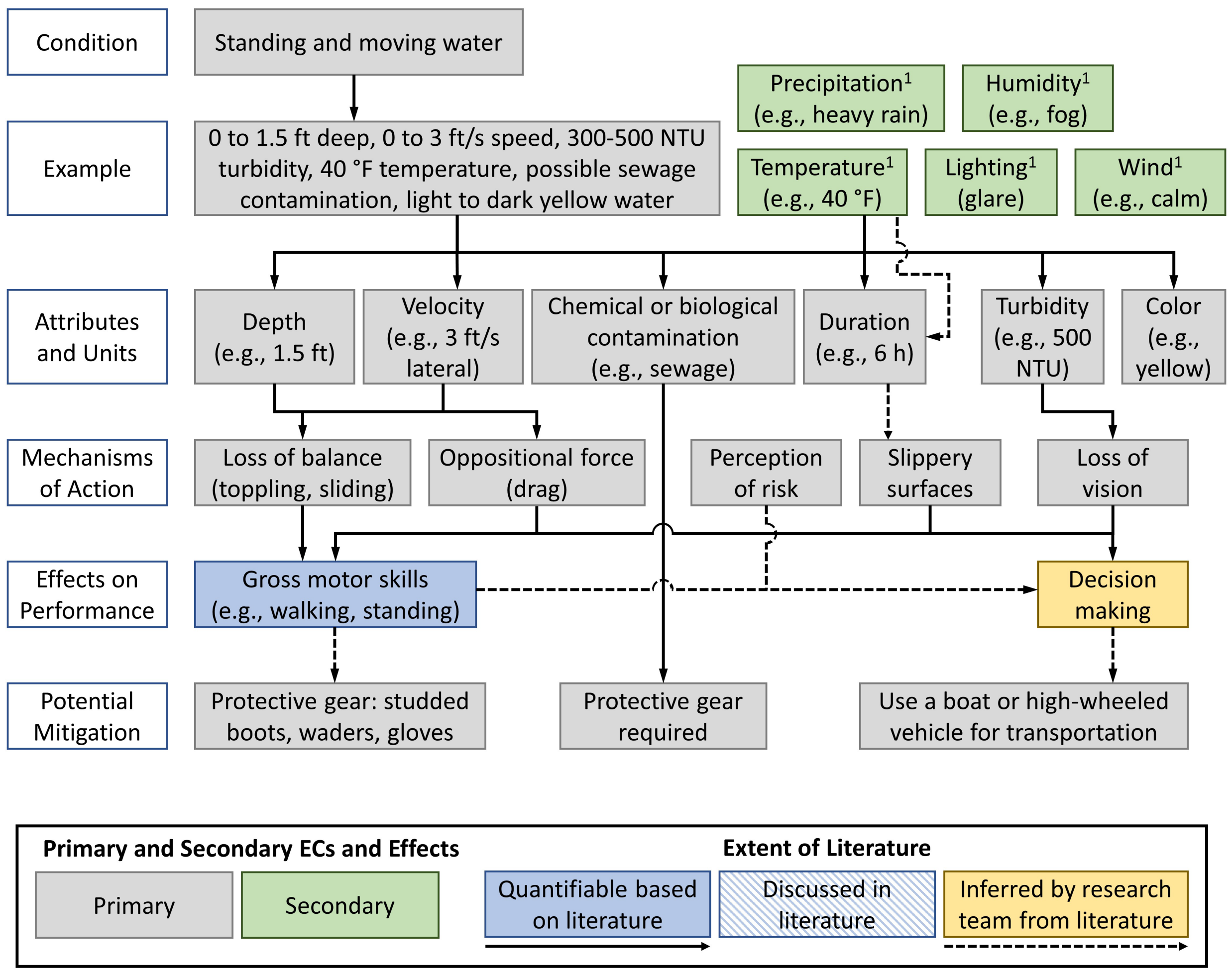
Personnel may encounter standing or moving water during execution of MAs if floodwaters inundate part of an NPP site. For example, this may variously occur when (1) precipitation accumulates in depressions (e.g., when an NPP drainage system is overwhelmed), (2) NPP areas are inundated by offsite floods, or (3) water remains in depressions after floodwaters recede. Standing and moving water attributes have potential effects on performance of MAs. Specifically, both the depth and velocity of floodwaters can affect individuals' stability, slowing execution of work, impeding movement, and, under certain conditions, even toppling personnel. At the same time, the EPA warns that floodwaters should be assumed to be contaminated by chemical and biological hazards and that personnel working in floodwaters should therefore wear appropriate protective gear. Noise associated with water flow, or ongoing precipitation, may disrupt communications and teamwork, though the magnitudes of such impacts may be difficult to characterize. The turbidity of floodwaters also may affect an individual's ability to walk confidently or perform underwater actions (e.g., lifting submerged items, working on objects that are underwater or partially submerged). The temperature of floodwaters also may have adverse effects on performance demands required for performing MAs (e.g., by affecting gross and fine motor skills and complex problem-solving skills; see also Chapter 2, Heat, and Chapter 3, Cold). Figure 10.1 provides an overview of standing and moving water attributes and impacts as well as their literature support levels and MA relevance.

10.2 Attributes and Units

Quantitative effects on MAs have only been studied for combinations of water depth and flow velocity. The depth of floodwaters is defined as the distance from a normally dry surface to the surface of the floodwaters. Depth, on the one hand, should be read with a limnimeter or a depth gauge, and is typically measured linearly in metric (cm, m) or English (in., ft) units. The velocity of floodwaters is a vector quantity defined by both water speed (cm/s, m/s, or ft/s) and direction, ideally with respect to the position of the individual. Water depth and velocity are typically considered in combination in recent empirical studies (e.g., with depth times velocity; referred to as the product number, expressed in m^2/s or ft^2/s). Together, depth and velocity are jointly predictive of the risk of toppling a stationary person (e.g., Abt et al., 1989; Lind et al., 2004; Russo et al., 2013; Xia et al., 2014). Combined water and personnel velocity may be used to estimate a nominal safe walking velocity (SWV) (e.g., Xia et al., 2014).

Chemical and/or biological contamination is commonly discussed as an attribute of floodwaters, but research is lacking to characterize its effects on the performance demands pertinent to the MAs addressed in this report. This is primarily due to the array of individual and contaminant combinations that might be present, which has led to a default requirement for protective gear. Chemical and/or biological contamination is measured by the amount of contaminant per count or volume (e.g., parts per million, g/L).

The turbidity and color of floodwaters are attributes that are obvious to individuals required to work in flooded areas. Silt, chemicals, and other particulates are swept along by the flow of moving water, and colloidal suspensions may be formed that create turbidity even in stationary water. However, formed, their presence tends to obscure the visibility of submerged objects and underlying surfaces. The common units of turbidity measurements are the Nephelometric



[1] See cold, heat, precipitation, humidity, lighting, and wind EC figures

Figure 10.1 Standing and moving water effects overview[1]

Turbidity Unit and Formazin Turbidity Unit, which measure the amount of light scattered 90 degrees to an incident beam directed at the water sample[2].

10.3 Time Variation of Standing and Moving Water

Depending on when an MA begins and how long it takes to complete, personnel may or may not be exposed to floodwaters. More importantly, because the water depth during a flood dynamically changes, individuals' exposures to this EC may also be variable in time. In other words, the severity of standing and moving water is time dependent and may vary significantly

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[1] Only some performance demands are listed here, as they may not be significant for the example condition.

[2] According to the U.S. Geologic Survey (USGS), Formazin Nephelometric Unit (FNU) and Nephelometric Turbidity Unit (NTU) both measure scattered light at 90 degrees from the incident light beam, but the FNU is measured with an infrared light source according to the ISO 7027 method, whereas the NTU is measured with a white light according to EPA method 180.1 (Anderson, 2005). USGS cautions that turbidity data collected with infrared light sources are not directly comparable to turbidity data collected with white light sources and care must be exercised when interpreting turbidity data that have different units of measurement.

over the duration of execution of a manual action or task (e.g., see variation in water depths for MAs 2 and 3 in Figure 10.2).

Figure 10.2 illustrates potential variations in water velocity and water depth during a flooding event. In this illustration, MAs (MA 1, MA 2, and MA 3) are portrayed as sequentially occurring with rising depth and velocity presenting a growing risk during MA 3. Weather and upstreamflood level reports may, or may not, provide useful information about the potential of near term depth velocity disruption. Statistical, probabilistic, and worst-case considerations consequently may be useful in analyses of standing and moving water during flooding events.

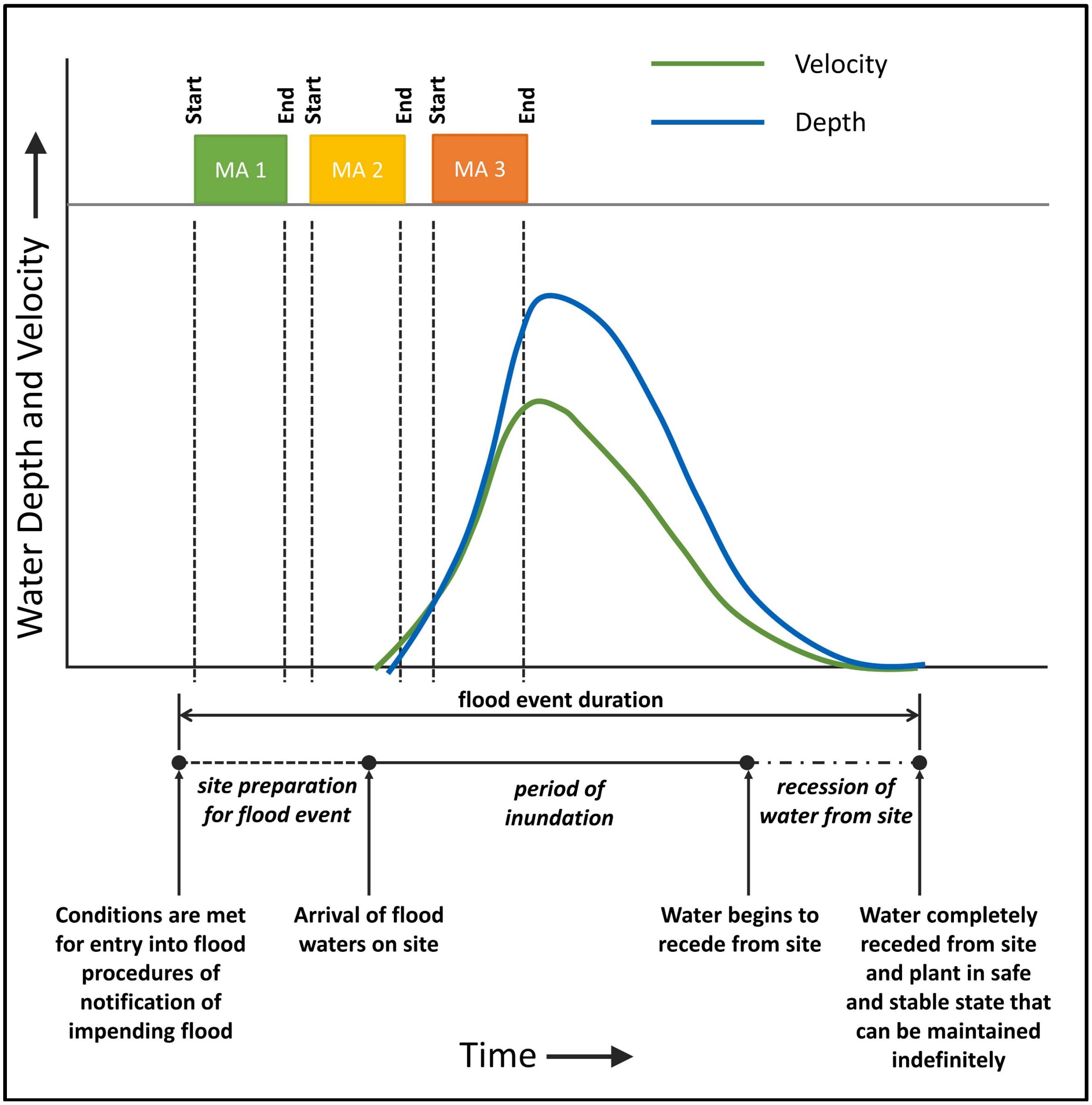

Figure 10.2 An illustration of standing and moving water variation during an example of a hypothetical flooding event

10.4 Mechanisms of Action

Water depth and velocity are the primary attributes for which there is literature describing predictable, quantitative MA effects. Standing and moving water can create a hazard for and slow or impede the movement of vehicles and create challenges for individuals working with manual tools by making them harder to place, manipulate, and recover[3]. However, the primary focus in the research literature has been on human instability, or loss of balance. Two types of instability have been identified as resulting from moving water (Jonkman & Penning-Rowsell, 2008): (1) friction instability and (2) moment instability. Friction instability, or the tendency for the human body to begin sliding, is more apt to occur with relatively shallow depths and relatively high-water velocities. Moment instability, the tendency for the body to topple over completely, is more apt to occur in relatively greater depths. Moment instability tends to follow friction instability (Xia et al., 2014). In practice, when workers are wearing appropriate flood protection gear (e.g., studded boots, waders), sliding will be reduced and the major impact of concern will be toppling.

The most obvious effect of turbidity on human performance results from its effect on vision. Increased turbidity reduces an individual's ability to see through the floodwaters to identify obstacles and anticipate and adapt effectively to changing terrain, identify and accommodate submerged objects, or recover dropped objects or tools. Effects of turbidity on MAs beyond those associated with obscured objects have not been a topic pursued in the research literature and may be a topic for future research. Webster et al. (2013) showed that moving water can generate perceptions of risk and associated fear and anxiety, especially when personnel do not have previous experience with the specific conditions.

10.5 Effects on Performance

As the combination of water velocity and depth (i.e., the product number) approach the toppling threshold, human performance is affected by difficulties in leaning over to lift objects, restricted range of motion, and limited dual hand activities, arguably because of the need to hold onto stationary objects. Other higher-level performance demands (e.g., fine motor skills, decisionmaking, detecting, and noticing), by logical extension, will be adversely affected if basic standing and walking are impeded by the velocity and depth of floodwaters. Although important, these higher-order effects are not formally quantified in the research literature. At greater flood depths and velocities, performance of any gross motor skills (e.g., standing or walking) becomes exceedingly difficult, because the body is sliding or toppling. Toppling into standing or moving water increases the probability of drowning, which is the cause of two-thirds of flood related fatalities (Sebastiaan N. Jonkman & Kelman, 2005).

10.5.1 Toppling and Instability

The most studied effect of water velocity and depth is toppling. When an individual is attempting to move or stand in standing or moving water, effort is required to maintain balance; this effort increases until the individual is unable to maintain balance and topples. At this point, life and limb are at stake and the individual ceases to make progress toward task completion. Absolute individual limits for velocity and depth have long been established as 3 m/s and 1.2 m, respectively (e.g., Russo et al., 2013).

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[3] Later, using Equation (10.2), the computation of the relative effects on walking speed are illustrated. Some analysts have "informally" suggested that this relative value for walking may be used to estimate times to complete associated manual handling tasks

10.5.2 Terrain Factors

Richmond et al. (2015) reviewed terrain factors related to walking and carriage that are arguably inter-related with friction instability and moment instability (Jonkman & Penning-Rowsell, 2008)[4]. These include: (1) slipperiness (i.e., amount of friction), (2) sinkage (i.e., depth of footprint), (3) roughness (i.e., how much twisting of foot or body is required), and (4) vegetation (i.e., how much it impedes travel). They note that sinkage and slipperiness are related to surface type, strength, and weather effects; whereas, roughness can be due to both natural (e.g., rainwater deposition) and human induced processes (e.g., plowing). Adding to Richmond et al.'s terrain factor list, for energy cost modeling purposes, are surface slope (percent), and velocity (m/s). Ultimately, Richmond et al. retain only these latter surface factors (i.e., percent slope and velocity), with all others embedded to develop empirically derived terrain factors (η) for an array of ~9 soil types[5]. The discussion by Richmond et al. (2015) illustrates the requirement for empirically driven global simplifications in order to achieve a useful gross motor model.

10.5.3 Simple and Complex Cognition

Webster et al. (2013) found perceptions of risk to influence participants' perception of water speed and other researchers have noted effects on cognition resulting from well-established stress and anxiety mechanisms (see Hancock & Desmond, 2001 for a review)[6]. At the same time, the additional workload associated with perceptions of risk for moving water, especially for inexperienced individuals, could lead to decrements in detecting and noticing, and understanding and decisionmaking, which have been shown in many other stressful or dangerous situations (see Bourne & Yaroush, 2003 for a review). The anxiety related effects of moving water on higher-level performance demands have not been examined quantitatively although they may be anticipated from the general neurochemical responses to perceptions of risk (see Lupien et al., 2007).

10.5.4 Recommended Limits

When the water depth velocity product number nears the point of toppling, it is unsafe for individuals to work standing or walking in the flood at all (see Figure 10.3). In Figure 10.3, the blue line represents an estimate of maximum values for safe work, based on an evaluation of the existing research literature. Specifically, the maximum values for safe work estimates are based on a conservative application of the Xia et al. (2014) incipient velocity of toppling (U_{ct}) model summarized below Equation (10 1)[7]. Specifically, the incipient velocity for toppling, U_{ct}, for an individual working in flowing water is:

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[4] Richmond et al. (Richmond et al., 2015) provide a comparative walk-through of a succession of models, based on progressively emerging data and analyses that begin with Givoni and Goldman (1971), who themselves built upon data and modeling reaching back more than 15 years.

[5] Methods for meaningfully assessing the four terrain factors identified by Richmond et al. (2015) have long plagued stability researchers. Regarding difficulties for even "slipperiness," see later discussion of the coefficient of friction in Section 6.11.2 on ice and snowpack. Empirically derived terrain factors (e.g., η) have continued to be employed as they have proven sufficiently stable as to be predictive.

[6] The neurochemistry and adverse cognitive effects of water-associated perceptions of risk may be anticipated to parallel those of activation, as experimentally explored with regard to thermal and other stressors (e.g., heat and cold).

[7] This Xia et al. (2014) model has its basis in considerations of the formal physics involved vs. the strictly empirical observation that toppling tends to be proportional to Product Number.

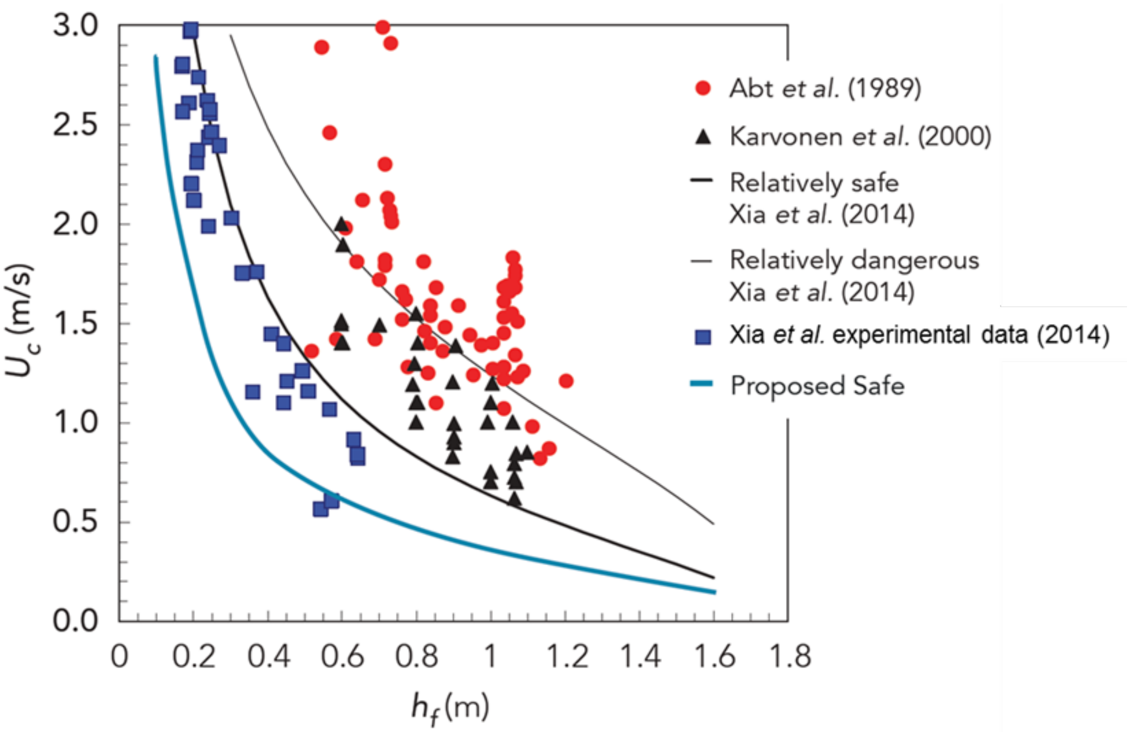

Figure 10.3 Empirical results and guidance for product number toppling effects (Adapted from Xia et al., 2014). Includes proposed safe guideline (bottom-most curve in blue).

$$U_{ct}=\alpha\left(\frac{h_f}{h_p}\right)^{\beta}\sqrt{\frac{m_p}{\rho_f h_f^2}-\left(\frac{a_1}{h_p^2}+\frac{b_1}{h_f h_p}\right)\left(a_2 m_p+b_2\right)} \quad (10\text{-}1)$$

where h_p = the height of the person (m),
h_f = the depth of flow (m),
m_p = the mass of the person (kg),
ρ_f = the density of the fluid (kg/m^3),
α = a coefficient estimated to be 3.472 m 0.5/s,
β = a coefficient estimated to be 0.188, and
$a_1, b_1, a_2 and\ b_2$= parameters estimated to be 0.633, 0.367, 1.015 × 10^{-3} m^3/kg, and -4.927 × 10^{-3} m^3, respectively.

In applying the U_{ct} model, a nominal height (h_p=1.8 m) and mass (m_p=82 kg) for the individual working in the flowing water were assumed. To conservatively accommodate variations from the nominal height and mass values, a safety factor of ~1/2 was applied. The utility of doing so is that it brackets the preponderance of individual results from Abt et al. (1989), Karvonen et al. (2000), and Russo et al. (2013).

These blue line maximum values for safe work can be used to estimate a threshold for a *SWV* (safe walking velocity), using the boundary equation:

$$SWV = U_c - V \tag{10-2}$$

Where U_c is the velocity (m/s) for depth of flow h_f (m) from Figure 10.3 and $V < U_c$ is the prevailing floodwater velocity (m/s).

In practice, individuals should assess both the prevailing and prospective flooding depth and velocity over the anticipated time of task performance and compare it with the results on Figure 10.3 (and computed SWV). If the prospective measurements meet at or above the safe blue line in Figure 10.3 or the computed SWV is inadequate to meet task performance time requirements, work on foot should not be attempted in the floodwater (see Section 10.6 for alternatives).

Example:

Problem: An individual has to walk 300 m to fetch required equipment. Estimate the effects of water that is 0.3 m deep and is flowing at 0.5 m/s on a person that normally walks at 1.34 m/s (~3 mph).

Solution: Using Figure 10.3, we project up vertically from the horizontal axis at h_f=0.3 m to intersect the blue line at the point with U_c≈1.0 m/s, which is twice the actual flow velocity; hence, there is minimal toppling risk. Using Equation (10 2), SWV = 1.0 m/s - 0.5 m/s = 0.5 m/s and the prospective time to traverse one way out (300 m) at 0.5 m/s would be 600 s (10 min). Normally walking at 1.34 m/s, the individual would be anticipated to make the same walk in (300 m ÷ 1.34 m/s) ≅ 224 s (~3.7 min). Therefore, considering toppling, the impact of the standing and moving water is to increase the baseline performance time, 3.7 min by 6.3 min, a 170 percent increase.

10.6 Potential Mitigation Measures and Their Effectiveness

Three levels of potential mitigations are available: strategic, informational, and individual.

10.6.1 Strategic

Planning ahead to avoid work in floodwaters likely represents the most effective mitigation approach (e.g., DHS, 2008; USACE, 2013)[8]. Ideally, external tasks can be completed before floodwaters arrive. When avoidance is not possible, conducting necessary work when the water depth and velocity are low (i.e., as early as possible) will mitigate the adverse effects. At modest water depths, temporary walkway emplacements may be an option and alternative means of transport (e.g., use of land or floating vehicles such as boats or even jet skis) may be able to provide transportation to critical task sites (which would ideally be elevated and/or surrounded by watertight barriers). In addition, prepositioned depth markers across the NPP site would facilitate assessment of viable transportation options as well as the danger of working on foot. It may also be possible to place land vehicles as temporary, partial shelters (partially interrupting flow) to protect workers on foot from the force of flowing water.

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[8] This follows the basic response to any oncoming threat situation, i.e., "do everything you can that is required before the threat arrives."

10.6.2 Informational

Training workers and reminding and encouraging them to exercise special caution when working in standing and moving water may mitigate some of the effects of standing and moving water. In keeping with training and information found effective in a related context (see Chapter 9, Precipitation)[9], cautionary steps (reminders) could include:

- Follow safety procedures.
- Wear appropriate and reflective clothing and use other methods to enhance the visibility of personnel and equipment.
- Monitor depth and appropriately reduce speed both when on foot and driving or operating heavy machinery.
- Double check work products.
- Enhance communication equipment and protocols to facilitate coordination and conveyance of information to workers in the field.

10.6.3 Individual

Protective outer gear is necessary for working safely in contaminated floodwaters (e.g., hooded anticontamination suit, with integrated nonslip over gloves, facewear, and nonslip footwear). Undergarments selected to enhance comfort, given seasonal conditions, can reduce the impacts associated with discomfort[10]. Adherence to decontamination guidelines following work in floodwaters is important for the individual worker's safety and for preventing the spread of contamination to others.

10.7 Interactions of Standing and Moving Water with Other Environmental Conditions

Standing and moving water conditions can co-occur with heat, cold, noise, lighting, humidity, wind, precipitation, and ice and snowpack conditions. Secondary conditions may include biohazards associated with chemical/biological contamination, slipperiness, and waterborne debris.

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[9] This approach has been found to be effective in moderating the effects of precipitation on accident rates (e.g., Rossetti & Johnsen, 2011).

[10] Full anticontamination suits, as described here, effectively add 10 °F to the experienced WBGT (see Chapter 2, Heat). This may be helpful in maintaining warmth on a cold day (see Chapter 3, Cold) but dangerously increase heat stress risks in warm weather (see Chapter 2, Heat).

10.8 Summary of Research on Standing and Moving Water Impacts

The state of the research literature addressing the effects of water on performance demands is summarized in Table 10.1.

Table 10.1 Standing and moving water effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(b) (c)
Sensation and visual recognition	3	(b) (c)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	3	(b) (c)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(b) (c)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	3	(b) (c)
Gross motor skills – heavy and light	1	(b) (c)
Other neurophysiological functions	3	(b)
Teamwork		
Reading and writing	3	(b) (c)
Oral face-to-face and electronic communication	3	(c)
Cooperation, crew interaction, and command and control	3	(c)

Assumptions and Limitations of Applicability

(a) Toppling risk is quantifiable for models, but individual toppling tendencies, depend on fitness and body dimensions as well as whether one is wearing loose or form-fitting clothing, shoes that have gripping abilities, etc.

(b) Perception of risk-associated anxiety regarding toppling can engender anxiety that limits attentional resources available for the range of perceptual, cognitive, and motor coordination capabilities (e.g., Lupien et al., 2007).

(c) It can be assumed that once an individual topples in moving water, other manual and/or cognitive tasks will cease to be performed.

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) *No information (a gap).*

11 ICE AND SNOWPACK

11.1 Introduction

Ice and snow are most often present at northern latitude U.S. NPPs, particularly during the winter, but they may also be present elsewhere at higher elevations. Figure 11.1 provides an overview of ice and snowpack attributes, their literature support levels, and MA relevance. When ice and snow reach the ground, the layer of frozen water provides a surface upon which slips and falls are dramatically increased. To maintain an upright posture in the presence of ice and snow, workers need to reduce locomotion speed and adjust gait and to use appropriate footwear to increase traction. In addition to being a slipping hazard, snow of several inches can also slow walking progress as a consequence of its “drag effect” on the feet and lower legs as well as concealment of potential tripping hazards. Preventive maintenance of walkways to remove tripping hazards and increase slip resistance (e.g., selective melt and/or sand and gravel applications) is helpful. When falling as a form of precipitation, ice and snow can substantially impair vision, especially for drivers of vehicles. When falling in the form of sleet, freezing rain, and/or snow, it can accumulate to block windscreens, obscure road signs, freeze up locks, and reduce the effectiveness of antislip countermeasures (see Chapter 9, Precipitation). Ice formed on equipment can impede operation and maintenance by blocking access and requiring removal. Snow and ice have other secondary effects via reflected sunlight, which can cause glare and even possible snow blindness (see Chapter 6, Lighting). The melting of large amounts of snow, often affecting the foothills of mountains, can produce dangerous secondary effects through moving water (see Chapter 10, Standing and Moving Water).

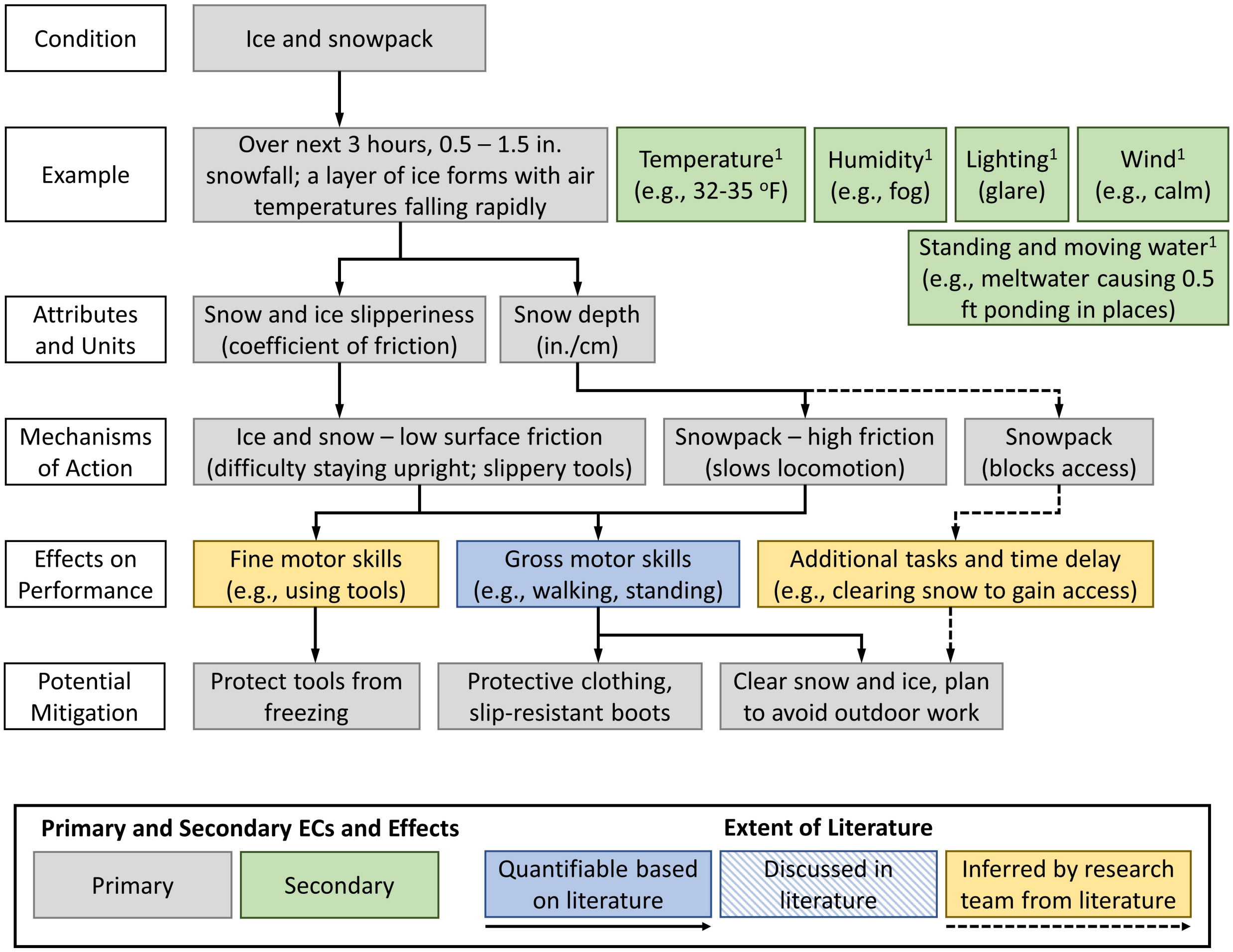
11.2 Attributes and Units of Measurement

Snow and ice are frozen water (the latter forms from the freezing of surface water and/or compression of snow). At temperatures below 32 °F (0 °C), pure water undergoes a state change from liquid to solid. The most problematic characteristic of ice for human performance is its slipperiness, which can be quantified in terms of its coefficient of friction for both static and dynamic conditions. The coefficient of friction can be measured in a variety of ways, but there are continuing issues regarding accessibility, reliability, and validity of the measurements, particularly for icy and snowy surface (e.g., Gao & Abeysekera, 2004). However, a static coefficient of friction above ~0.2 has long been suggested as the minimum for slip-free walking on a level, dry surface. Gao and Abeyskekera (2004), however, noting the lack of definitive recommendations for a coefficient of friction greater than 0.5, point to the need for future research to resolve the issue. Nevertheless, it is clear that any surface with a static coefficient of friction less than 0.2 likely presents a slipping hazard.

Snowpack is snow accumulated on the ground, which distinguishes it from snow falling through the air as precipitation (see Chapter 9, Precipitation, for a discussion). Its depth (measured in inches or centimeters) and density (measured in lb/ft^{t3} or kg/m^3) are characteristics relevant to performance demands. Very densely packed snow (approaching ice density) also can become slippery; thus, snow’s coefficient of friction maybe also be relevant.

11.3 Time Variation of Snowpack and Ice

Figure 11.2 illustrates the complexities of potential variations in the presence of snowpack and ice and the associated depth as a function of possible floodwater inundation. Snowpack may be present and ice may form before the flood arrives on the site. Snowpack and ice on surfaces



[1] See cold, humidity, lighting, wind, and standing and moving water EC figures

Figure 11.1 Ice and snowpack effects overview.[1]

inundated by floodwater may melt but may persist on other surfaces. In this illustration, MAs (MA 1, MA 2, and MA 3) are portrayed as potentially occurring under a wide variety of possible snowpack depths (and variation may be possible within each MA). Statistical, probabilistic, and worst-case considerations consequently may be used during analyses of required interventions to address prospective future flooding events where snowpack and ice conditions may be present.

11.4 Mechanisms of Action

The primary mechanisms of action for ice and snowpack involve slipping and drag, although snowpack can obscure pathways, road signs, landmarks, and equipment. The research team did not find any studies addressing the obscuring effects of snowpack or perceptions of risk regarding individuals’ reactions to the potential for slipping, falling, and injury, but these have been shown to be important in similar environmental contexts (see Chapter 8, Wind, and Chapter 10, Standing and Moving Water).

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[1] Only some performance demands are listed here, as others may not be significant for the example condition.

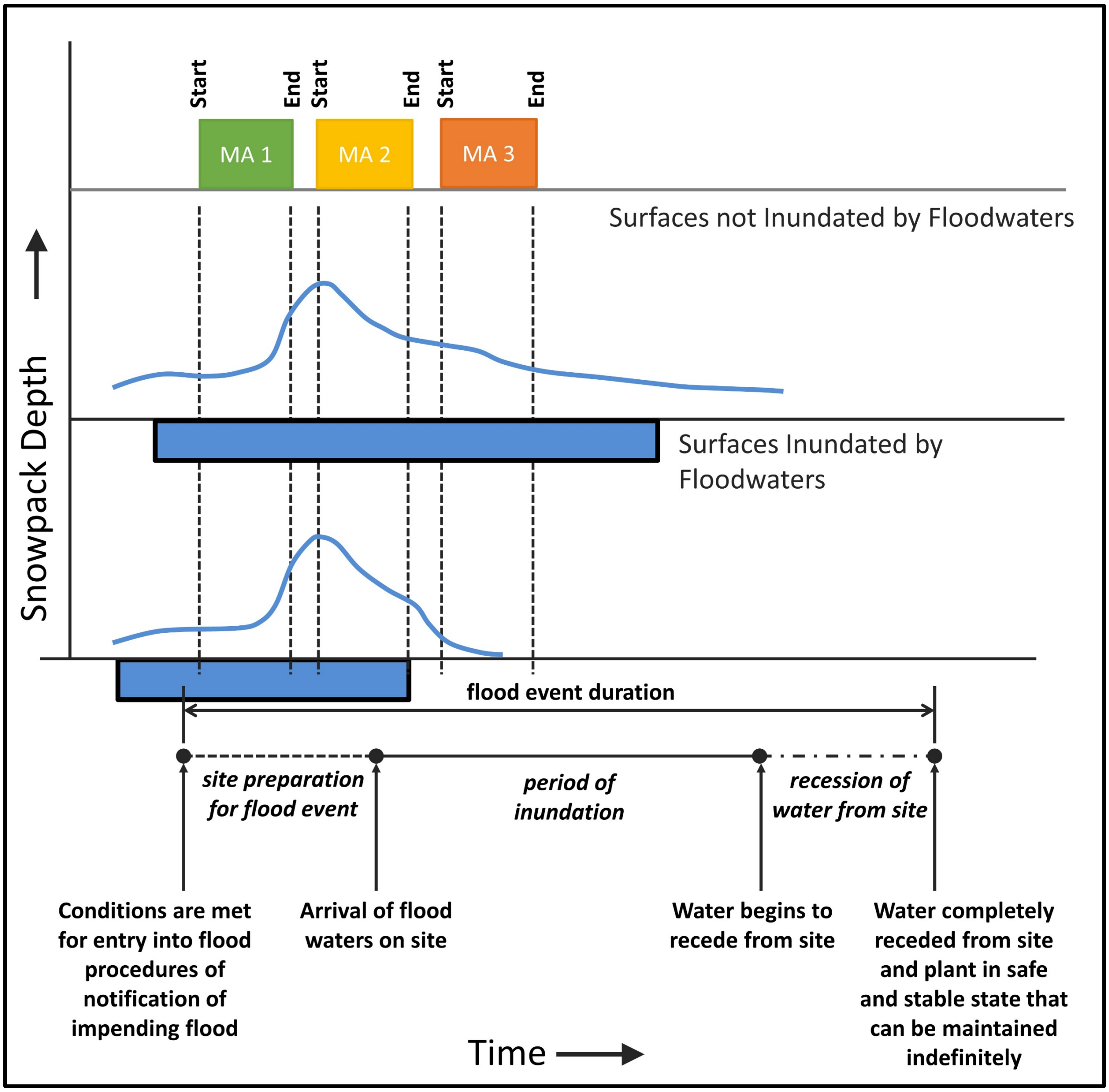

Figure 11.2 An illustration of ice and snowpack variation during an example of a hypothetical flooding event

11.4.1 Slipperiness and Slipping

The slipperiness of outdoor walking surfaces when snow and ice are present is a factor in many outdoor winter accidents. Slipperiness, or “conditions underfoot which may interfere with human beings, causing a foot slide that may result in injury or harmful loading of body tissues due to a sudden release of energy” (Grönqvist et al., 2001)[2], is the characteristic of ice and snow that cause slipping. Slipping has been defined (Grönqvist, 1995) as “a sudden loss of grip, resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity, often in the presence of liquid or solid contaminants” (e.g., ice, snow). Slips

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[2] Slipperiness is not limited to ground surfaces. Ice coating on objects can make them slippery. A surface or object is slippery when it is difficult to hold firmly or stand on because it is smooth, wet, or slimy.

account for up to 85 percent of all fall related occupational injuries (Courtney et al., 2012). Common injuries as a result of slipping on ice and snow include sprains and fractures of the wrists, pelvis, hips, legs, and ankles. The most common injuries due to slips and falls are to the lower extremities (33 percent of slip-fall injuries). However, back injuries are also quite common (23 percent of falls) (Yoon & Lockhart, 2006). Slip-and-fall injuries are particularly likely to occur among outdoor workers (Bentley, 1998).

The precipitating factor for most slips on ice and snow is low friction between the ice or snow surface and footwear (Gao & Abeysekera, 2004; Grönqvist & Hirvonen, 1994). As noted above, the tendency of a surface to resist slippage is measured by its coefficient of friction. This is the result of the interaction between the coefficient of friction of the ice or snow itself and those of the parts of footwear that come in contact with it. As also noted above, the minimum coefficient of friction for safe walking is 0.2 on a flat surface (Shintani et al., 2003). Higher friction coefficients are required to successfully traverse sloped surfaces.

Ice and snowpack can vary in slipperiness or coefficient of friction (Gao & Abeysekera, 2004; Petrenko, 1994). Ice is at its slipperiest when a thin water layer is present on its surface, usually near 32 °F (0 °C). When stepping on ice, a very low coefficient of friction between ice and footwear materials occurs when frictional heating from the pressure of the footwear melts the surface of the ice (Bowden & Hughes, 1939). This creates a thin film of water, which causes the surface of the ice to become slipperier. This is the effect that makes ice skates glide so well

Researchers have found that the heel and sole of footwear play the greatest role in determining grip and, consequently, slippage (Gao & Abeysekera, 2004). When friction between the heel and sole and the ground (ice or snow surface) is very low, the chance for slippage increases. The most important point in one’s gait for slip-related falls is when the heel strikes the surface (Grönqvist & Hirvonen, 1994), followed by when the toe is in the process of leaving the surface. In both cases, slippage occurs on ice and/or snow because it is at these points that the largest transfer of weight is occurring across the smallest surface area (Redfern et al., 2001). When a low coefficient of friction is encountered at these points, a worker has only approximately 1/10th to 1/5th of a second to recover before a fall (Strandberg & Lanshammar, 1981). As the heel begins to slip, whether the worker falls or not depends on that worker’s ability to make recovery movements to regain balance, which may take up to 1/5th of a second for the average adult (Strandberg & Lanshammar, 1981). Even when workers are able to react in time to avoid a fall, they often injure their lower backs as a result of the movements made trying to regain balance (Rashedi et al., 2012).

Thaw-freeze cycles can make snow more problematic with respect to slipping. Merrild and Bak (1983) found that pedestrians suffered slip-and-fall events 14 times as often during days when daytime temperatures rose well above 32 °F (0 °C) and nighttime temperatures dropped back below freezing than when the daytime temperature remained close to or below freezing. The snow thaw caused by the higher daytime temperatures produces free water, which then freezes again into relatively smooth ice as nighttime temperatures fall below freezing. Ice amid snow (on top of or underneath it) may not be visible and may therefore be unexpected. Workers walking on snow may therefore not be as cautious as they are when navigating an icy path, increasing their likelihood of slip-and-fall incidents.

Slip-and-fall risk appears to be influenced by a worker’s awareness of the potential slipperiness, and snow-covered ice is one of the leading causes of slip-and-fall accidents. When pedestrians are aware of an ice patch, they usually take defensive actions, such as shortening strides, slowing speed, and stepping flatter footed. This reduces the forces at work between footwear and the ice or snow surface (Cham & Redfern, 2002; Gao & Abeysekera, 2004) thereby increasing the effective coefficient of friction and helping to avoid a slip. The tendency for pedestrians to walk faster in inclement weather (Martin et al., 2000), which increases the probability of slipping, may act to counteract this slip-reducing response. Exploring the relationship between these two responses is another potential area for future research.

11.4.2 Drag Due to Ice and Snow

Drag caused by snow can also hinder pedestrian and vehicular travel, as anyone who has walked through snow after a major snowstorm can attest. The deeper and denser the snow, the higher the friction drag between the snow and the feet and legs. This increased resistance slows walkers and requires them to expend more energy to complete the same actions. For example, walking through low-density, fluffy snow at a depth of about 14 inches is about four times as metabolically demanding (i.e., maximum volume of oxygen [VO2] required) as walking on dry blacktop (Pandolf et al., 1976). This fourfold difference is predictive of walking speed, given the tendency of individuals to maintain VO_2 (as reflected in Figure 11.3).

11.4.3 Secondary Mechanisms

Secondary effects of ice and snow involve light and standing and moving water (for details see Chapter 6, Light, and Chapter 10, Standing and Moving Water). Both snow and ice can reflect a great deal of light, producing significant glare. Constant exposure to sunlight reflecting off snow can also cause snow blindness (i.e., photokeratitis), because the increased exposure to the sun's UV rays essentially causes a sunburn to the cornea of the eye. The other major secondary effect of snow results when large amounts of snow melt and create standing and/or moving water. Snowmelt speeds up as the temperature increases beyond 32 °F, which can produce sufficient water to overwhelm street drainage and affect workers on foot and driving.

11.5 Effects on Performance

Falls from slipping and tripping while walking constitutes the majority of industrial accidents. They are the cause of up to 15 percent of deaths resulting from accidents, and follow only vehicles crashes as a cause of fatalities. Studies of snow- and ice-related accidents, such as that conducted by Hassi et al. (2000), have shown an inverse relationship between injury rates and ambient temperatures. This association of cold temperature with accidents is not completely linear, however, because the strongest association occurred at temperatures of around 36 °F and below (Hassi et al., 2000). Slip-fall injuries on snow and ice are especially common for outdoor occupations (e.g., mail delivery, mining, construction) (Gao et al., 2008). Carrying a load while walking interferes with postural stability. Indeed, even holding a load adversely affects postural stability in rough proportion to its weight and height (Davis, 1983; Leamon, 1992). Models of load carrying walking speeds, which include slope effects, assign a terrain factor of 1.7 for hard snow vs. 1.0 for dry pavement (Richmond et al., 2015, Table 11)[3]. Two-thirds of all slip-fall events happen on ice covered with snow, which is likely associated witha failure to modify walking strategy because the individual did not perceive the risk (Cham & Redfern, 2002; Gao et al., 2008).

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[33] Terrain factors, in this context, may be viewed as the relative cost of walking (or carriage) beyond a baseline from simply standing unburdened (or with a load) to take into account, for example, the difference in effort required to walk up an incline.

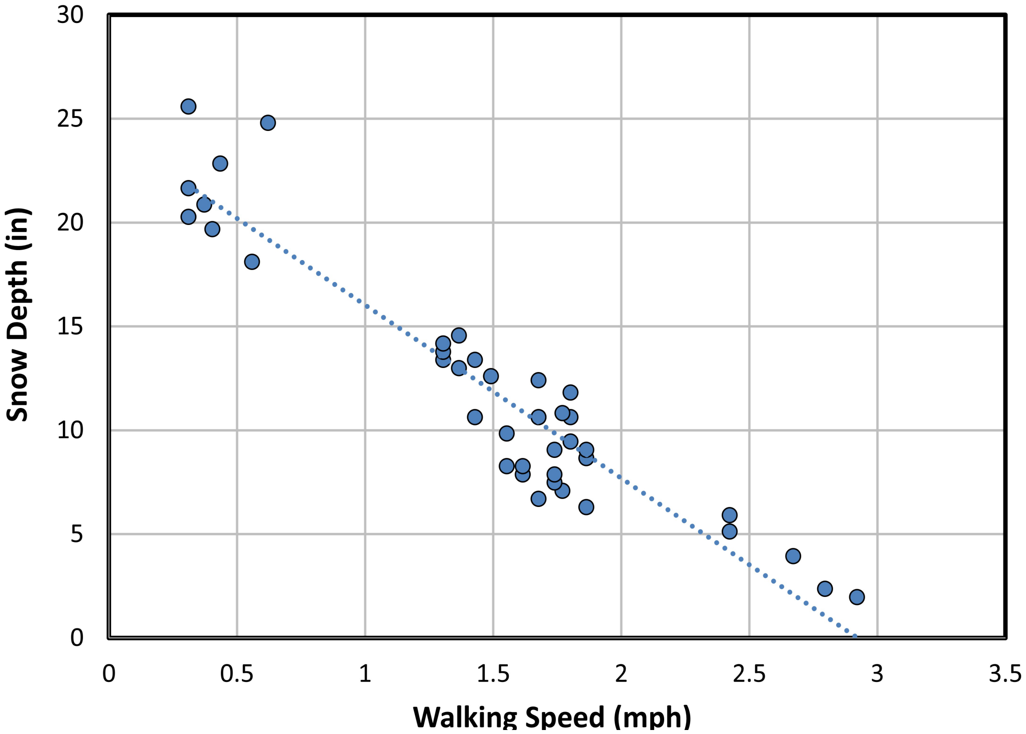


Figure 11.3 Impact of snow depth on walking speed (Adapted from Ramaswamy et al., 1966)

11.5.1 Gross Motor Skills and Effort

Ramaswamy et al. (1966) demonstrated that snow depth has a linear relationship with oxygen consumption, energy expenditure, and walking speed. Data excerpted from this study were used to create a regression equation (see Figure 11.3) that predicts the effect on walking velocity, V_w, of a given snow depth, d_S ($R^2 = 0.89$). Arguably, the speeds of manual handling (nonwalking gross motor) tasks might be anticipated to follow essentially the same function. Workers should avoid walking for long periods through snow to avoid slip-fall accidents and frostbite to feet (see Chapter 3, Cold). However, if there is no alternative, the following equation can be used to estimate the effects of snow depth on walking speed (as well as relative manual handling task speeds):

$$V_w = -(\frac{10((1000 * d_s) - 24371)}{83389}) \tag{11-1}$$

where V_w is walking speed (mph) and ds is snow depth (in.).

The presence of hard snow and ice also appears to alter walking speed when subjects are aware of its presence. For example, in addition to the finding of Richmond et al. (2015, Table 11) discussed above, participants in a Japanese study (Shintani et al., 2003) decreased their walking speed from an average of about 3 mph on a non-icy surface to about 2.5 mph when walking on ice with a coefficient of friction under 0.2 (the critical value for safe walking). That is, they decreased their walking speed by approximately 20 percent. The speed of individuals walking in the presence of ice in this study is comparable to the high end of the speed of individuals walking in snow (as shown in Figure 11.3). However, the reason for this effect is not drag as it is with snow, but rather intentional care resulting from knowingly walking on ice. Richmond et al. (2015), although not directly addressing either of the surfaces examined in the study by Ramaswamy et al. (1966) or Shintani et al. (2003), appear to provide a way to address the range of ice and snowpack conditions.

Vehicle speed is also slowed by snow, but this is most likely due to caution on the part of the driver concerning the ability to steer and brake. For example, Kyte et al. (2001) found that in the presence of snow covered pavement free flow vehicle speed was reduced by approximately 16 km/h or 10 mph (13 percent) from the free flow speed during ideal conditions. Similarly, Perrin et al. (2001) found reductions in free flow speed of 25 percent for conditions involving wet and slushy pavement, and 30 percent for slushy wheel paths. It should be noted that in these studies the conditions were qualitatively described rather than quantitatively measured (e.g., 6 inches of snow-ice mix). Consequently, actual modifications in vehicle speed may vary significantly from these values, depending on snow depth.

Storms producing heavy snow and ice can cause delays and road closures and produce driver control problems such as loss of traction and visibility. This is especially problematic for black ice, which blends visually with the pavement, thereby preventing awareness (similar to ice covered snow when walking) and consequently, caution. This can produce catastrophic loss of control (Rossetti & Johnsen, 2011).

Finally, shoveling snow to clear walkways or areas around equipment can be an especially strenuous activity, because of the combined effects of cold, significant muscular strain, and the potential for slip-fall events. The potential for exhaustion, dehydration, lifting related back injuries, slip-fall injuries, and heart attacks from snow shoveling is significant enough that OSHA has produced advisory pamphlets on the subject (e.g. OSHA, 2016a).

11.5.2 Recommended Limits

Aside from the OSHA snow shoveling advisory, the review did not find any recommended limits specific to working in ice and snow.

11.6 Potential Mitigation Measures and Their Effectiveness

Prompt clearing of foot and vehicle traffic areas of snow and ice, using appropriate slip-resistant boots and correct lifting techniques where shoveling is necessary, reduces the probability of slips and falls. Salting can serve as an aid in melting snow that is difficult to remove, and sanding can provide additional friction. Avoiding icy and snow-covered areas whenever possible and increasing vigilance about the condition of walkways can reduce the likelihood of workplace injury. High traction footwear and walking sticks may be helpful in avoiding falls. Individual workers can do the following to reduce their chances of slip-and-fall injuries on ice and snow:

- NIOSH recommends (Bell et al., 2010) that proper slip-resistant winter footwear be worn when outdoor work is unavoidable. Snow boots with soft heel and toe materials tend to show better slip resistance than hard materials for walking in snow, but for ice with a thin layer of water, or ice near freezing point, boots with hard, sharp cleats are recommended (Grönqvist, 1999). Crampons, employed by outdoor enthusiasts, may serve the same purpose, when worn over work boots. Explicit care should be taken when transitioning between snow and ice and non-slippery surfaces (e.g., cement steps, metal platforms), because cleats have been associated with slips at transitions of this type.

- Outdoor workers can also make traversing icy areas safer by walking at a slower pace and taking shorter steps (Grönqvist, 1999).
- Use of sand and gravel on ice produces some slip resistance on wet ice, but it does not have a clear effect on dry ice (Grönqvist, 1999). However, in some studies, participants have claimed they felt safer on graveled ice than when wearing anti-slip shoes, despite the fact that the coefficient of friction was lower on graveled ice (and thus the slip danger was comparatively greater) (Shintani et al., 2003). Thus, the presence of graveled ice may be counterproductive, causing workers to underestimate the danger involved.

The snow hazard can be mitigated by: (1) removing snow immediately following a storm from parking lots and routes, (2) salting and sanding particularly difficult-to-clear spots, and (3) closing and marking particularly dangerous pathways and roads to avoid injuries. Because drivers may lose control of their vehicles on snow and ice, worker safety can be increased by properly setting up traffic controls, warning signs, cones, barrels, and/or barriers in outdoor work zones near parking areas or roads and by having workers wear appropriate reflective vests when near parking lots or roads at night so that drivers can see and react to them.

OSHA has the following further recommendations for drivers of automobiles, forklifts, and other heavy machinery in snow and ice (OSHA, 2016b):

- During the daylight, rehearse maneuvers slowly on ice or snow in an empty lot.
- Steer into a skid.
- Understand the braking mechanisms inherent to your vehicle. To stop a skid, stomp on antilock brakes, but pump non-antilock brakes.
- Plan to use longer stopping distances on ice and snow.

Guidance for outdoor work activities, when removing snow manually, include the following:

- Warm up musculature before the activity, as if you are preparing for exercise.
- Scoop small amounts of snow at a time when manually moving snow.
- Whenever possible, push the snow instead of lifting it.
- When lifting is necessary, use proper lifting techniques: keep the back straight, lift with the legs, and avoid turning or twisting the body (OSHA, 2016a).

11.7 Interactions of Ice and Snowpack with Other Environmental Conditions

Snow and ice usually occur with cold, and sometimes wind. Ongoing snow and ice production can co-occur with precipitation. Secondary effects of snow and ice include glare and snow blindness (see Chapter 6, Light), and flooding (see Chapter 10, Standing and Moving Water).

11.8 Summary of Research on Ice and Snowpack Impacts

The current state-of-knowledge regarding the effects of ice and snow on performance demands is summarized in Table 11.1

Table 11.1 Ice and snowpack effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	2	(d)
Sensation and visual recognition	2	(d)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	3	(d)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(d)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	2,3	(c)(d)
Gross motor skills – heavy and light	1,3	(a)(b)
Other neurophysiological functions	4	(d)
Teamwork		
Reading and writing	2	(d)
Oral face-to-face and electronic communication	3	(d)
Cooperation, crew interaction, and command and control	3	(d)

Assumptions and Limitations of Applicability

(a) The quantitative impact of snow depth on walking speed is summarized in Figure 10.3.

(b) Some limited information about walking speed effects of both hard snow and ice with a sub-0.20 coefficient of friction has been shown. Both load weight and height have been shown to directly impact standing steadiness.

(c) At least to the extent that driving at a constant speed requires discrete and continuous motor skills, there is some limited information about ice and snow impacts on free-flow driving speed.

(d) Snow/ice—in daylight—may serve to directly disrupt visual performance at all levels and thereby dependent and downstream tasks. Perceptions of risk might be anticipated to have impacts similar to standing/moving water (Lupien et al., 2007).

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) *No information (a gap).*

12 LIGHTNING

12.1 Introduction

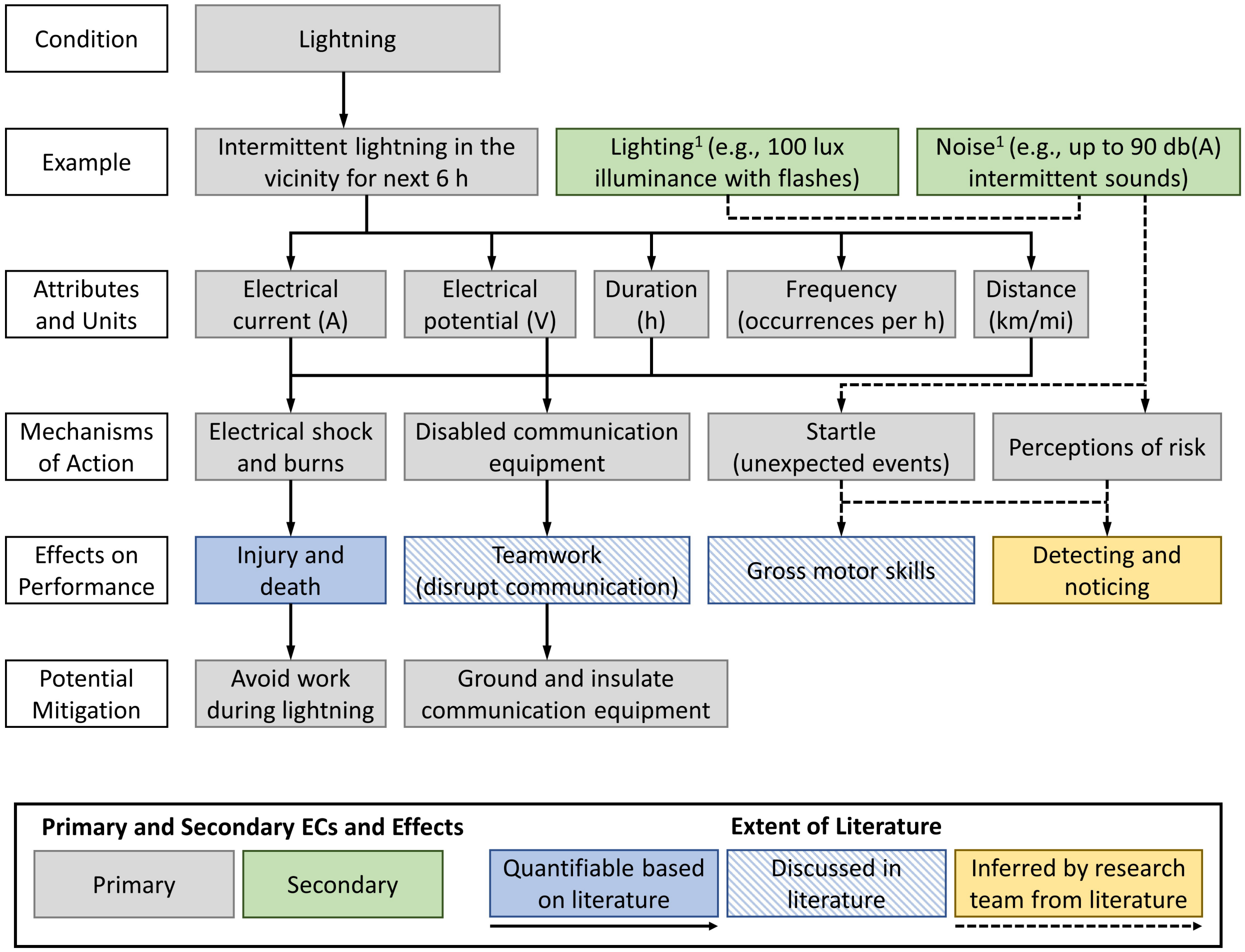
Lightning is an electrical discharge. As thunderclouds move above the Earth's surface, they build up a static charge (i.e., negative on the bottom and positive on the top). The negative charges in the cloud attract positive charges at the top of the cloud, in other clouds, and on the ground beneath the cloud. The oppositely charged regions induce an electrical field. Channels of ionization propagate through the air between these charged areas. When the charge is strong enough to overcome the insulating effect of the atmosphere, these ion channels connect, providing a discharge path for the electric potential difference. Lightning strikes occur when the connecting channels link the cloud with the ground or objects connected to the ground.

12.2 Attributes and Units of Measurement

Thunder occurs with lightning, as the discharge induced ionized gas, undergoes a rapid increase in temperature and pressure, expanding explosively outward from the discharge and then contracting rapidly as it cools. The shock wave created by the expansion is experienced aurally as the initial crack of thunder, followed by rumbles from the continuing vibration of the air column (NOAA-NASA, 2016; NWS, 2010). During a storm, between 70–90 percent of lightning occurs between and within clouds, where it presents a minimal threat to those on the ground. Consequently, thundercloud-to-ground lightning represents a threat to humans only for 10–30 percent of the lightning produced during a storm. Cloud-to-ground lightning can cause injury or death from a direct strike to an individual via many possible paths. These include transmission of the electrical charge to the individual through ground conduction, ground wires, or metal objects (e.g., heavy equipment), as well as by fires started by lightning and objects toppled by lightning. Apart from its health-related effects, lightning can significantly affect electronic communication and electrical grids, which can disrupt command and control abilities. Lightning and thunder can also produce startle effects in people through the sudden appearance of bright flashes and loud noise (see Chapters 6, Lighting, and 4, Noise). Cloud-to-ground lightning strikes occur approximately 30 million times per year (Cooper & Edlich, 2016), and nearly 75 percent of strikes occur in the summer months (i.e., June, July, and August in the Northern Hemisphere). Lightning is the second leading cause of storm related deaths in the United States, after floods (Roeder, 2008)

Because of the danger lightning poses to worker safety, little research has been conducted on the effect of lightning on worker performance in field settings. Instead, efforts have been focused on ensuring that workers are not exposed to the danger of lightning, clearing outdoor work areas well before lightning occurs, and postponing unsheltered work when lightning is likely. Its frequency (measured in strikes or strikes per minutes) are characteristics relevant to performance demands However, experimental studies of the effects of unexpected loud noise and bright flashes have shown that they distract from ongoing cognitive and other tasks and induce a motor slowing response that occurs via brain mechanisms for action stopping (Parmentier, 2014; Wessel & Aron, 2013). Figure 12.1 provides an overview of lightning attributes, their literature support levels, and MA relevance.

Figure 12.2 displays lightning distribution over time during a hypothetical thunderstorm. In this illustration, MAs (MA 1, MA 2, and MA 3) are portrayed as occurring during periods of lightning (when frequent complete work stoppage and/or sheltering may be required to moderate risk). Weather reports may, or may not, provide predictions of the short-term risks of area lightning



[1] See lighting and noise EC figures

Figure 12.1 Lightning effects overview[1]

strikes and local monitoring may be required to ensure safety during storms. Statistical, probabilistic, and worst-case considerations consequently may be used during long term planning where lighting is an issue.

12.3 Mechanisms of Action

Though each lightning bolt is only approximately 1–2 inches wide, single bolts of lightning carry approximately 300 million volts at about 30,000 amperes. Lightning produces local heat that can exceed 50,000 °F, which is ~3 times hotter than the surface of the sun. Lightning discharges travel at a speed of about 90,000 miles per second (IOSH, 2011). Thunder, the shock wave created by superheated air in the lightning channel, travels at the local speed-of-sound (~1,000 ft/s). Consequently, the time difference in seconds (Δt) between seeing a lightning flash and hearing thunder can be used to estimate the lightning's distance from an observer (D = ~1000 Δt). Louder and/or increasingly frequent thunder and lightning activity corresponds to increased

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[1] Only some performance demands are listed here, as they may not be significant for the example condition.

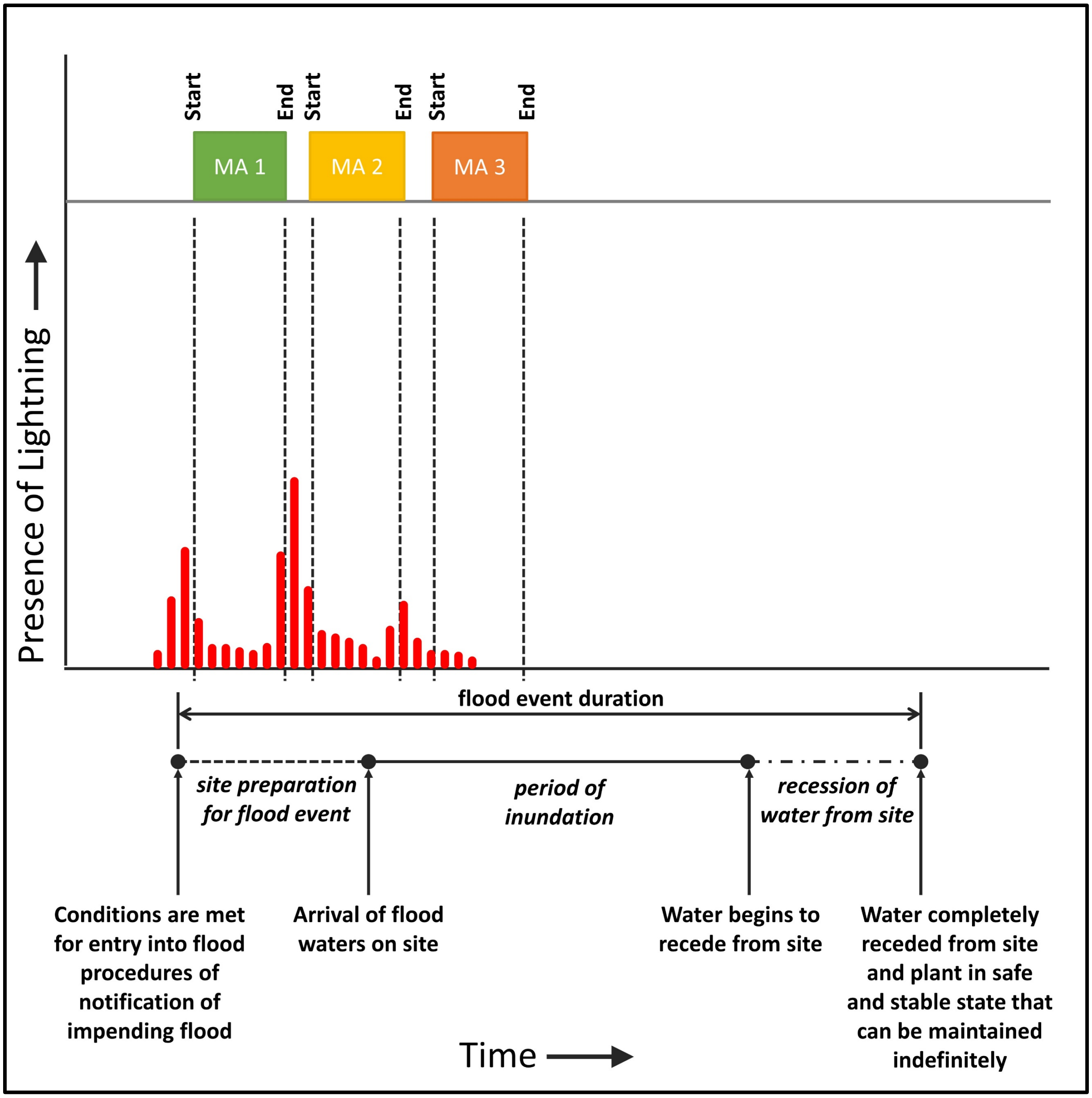

Figure 12.2 An illustration of lightning variation during an example of a hypothetical flooding event

risk of lightning injury or death to exposed individuals. Thunder, which co-occurs with lightning, is experienced as a loud noise (see Chapter 4, Noise).

Thunder, as an unexpected auditory stimulus, can distract from ongoing cognitive and other tasks and can induce a motor slowing response due to the brain mechanisms that stop action following unexpected events (Parmentier, 2014; Wessel & Aron, 2013)[2]. Damage from lightning can arise from the electrical power and associated heat. As noted by Cooper and Edlich (2016), three factors increase an object's vulnerability to a lightning strike: (1) the object's height (taller

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[2] Sudden unexpected bright flashes appear to have similar effects (see Section 6.6, Lighting).

is more likely to be struck); (2) its isolation (isolated is more likely to be struck); and (3) its pointedness (taller and thinner objects are more likely to be struck). Only about 3–5 percent of lightning related injuries are due to direct strikes; the vast majority are transmitted indirectly to the victim through a primary strike of another object (Cooper & Edlich, 2016).

Lightning can affect people in various direct and indirect ways. When lightning directly strikes an individual, it typically causes cardiac and/or respiratory arrest as well as neurological damage. People may also be affected by a sideflash in which the body provides a parallel path to the ground for the electrical current from the primary strike of an object. If the current passes through the head or heart on the way to ground, death may quickly result. Lightning victims who have survived often face life long debilitating injuries and chronic pain from burns, neurological and cardiopulmonary damage, brain and spinal cord damage, as well as hearing and eye damage (Cooper & Edlich, 2016). Conducted current can also spread from a strike on a poorly grounded electrical pole or wiring system to a nearby person. This can result in anything from a tingling shock to a large current through the body. Similarly, step voltage radiates out through the ground itself from an object (IOSH, 2011) to an affected individual. Step voltage effects cause many livestock deaths every year. Lightning can also indirectly cause severe injuries and even death from resulting fires and exploding and falling trees or other objects.

Electrical discharges from lightning strikes can also affect sensitive electronics, disrupting communication equipment such as walkie talkies and radios. Power overloads at electrical substations (as well as fallen trees) can knock out power distribution, disrupting communications that rely on electricity.

12.4 Effects on Performance

Apart from the risk of serious injury and death to workers, disruption of communications represents lightning's most reported direct effect on performance (e.g., disabling walkie talkies, computers, telephones or requiring workers to avoid their use). Travel time by foot or vehicle can be affected when lightning disrupts lighting, traffic signals, and other traffic control devices (FHWA, 2004). Secondarily, thunder and dazzle effects of lightning, which are unexpected auditory and visual stimuli, can distract from ongoing cognitive and other tasks and temporarily slow motor actions (see Chapter 4, Noise and Chapter 6, Lighting) (Parmentier, 2014; Wessel & Aron, 2013). No studies were found that quantified these effects in terms of either increased time or increased error rates. This is in part because of concern about worker safety leading to termination or rescheduling of outdoor work in the presence or threat of lightning, and the difficulty of conducting laboratory tests that simulate specific exposure to lightning. Nonetheless, especially for those caught outside during close strikes, lightning associated perceptions of risk could be anticipated to result in both neurochemical changes and performance disruptions that parallel those for other perceptions of risk inducing stressors (see Chapter 8, Wind, and Chapter 10, Standing and Moving Water). Lightning can also produce secondary effects on humans through associated lighting and noise, often in the presence of wind, and precipitation.

12.4.1 Recommended Limits

There is no recommended minimum amount of lightning. Lightning should be avoided entirely. Safety from lightning suggests a 30 min delay in outdoor work activities in the presence of lightning.

12.5 Potential Mitigation Measures and Their Effectiveness

Unlike other ECs such as heat and cold, there is no safe amount of lightning that would allow outdoor work to proceed in the presence of lightning (contrary to many long-held rules of thumb). Indeed, the NWS states that when lightning is visible, or thunder is heard, work should immediately cease and workers should move to a safe location (NWS, 2010). Roeder et al. (2012) note that widespread failure to follow this pattern of avoidance is responsible for lightning being the second leading cause of storm related deaths in the United States (following only floods)[3]. Along with their colleagues Cooper and Holle (2012), Roeder et al. (2012) recommend coordinated informational programs regarding lightning's risks and delineated ways to protect workers. Table 12.1 illustrates their basic summary of safe practices. Each of the five levels of safety contain more detailed recommendations[4]. An essential part of a lightning safety plan is informational and training programs that teach workers about the risks of lightning and appropriate responses to lightning events.

Table 12.1 Summary of the five levels of protection

Quick Reference for the Five Levels of Lightning Safety		
Fundamental Principle: **NO place outside is safe, when thunderstorms are in the area!**		
Best to Worst	**Level**	**Brief Description**
	1	Schedule outdoor activities to avoid lightning
	2	Know when and where to be in a safe place. When thunder roars, go indoors! Half an hour since thunder roars, now it's safe to go outdoors Safe places are a large fully enclosed building with wiring and plumbing, e.g., house, school, store. etc., or a vehicle with a solid metal top and solid metal, e.g., most cars, trucks, or buses.
	3	Avoid dangerous locations/activities (elevated places, open areas. tall isolated objects, and water related activities [swimming, boating, near edge of bodies of water]). Do <u>NOT</u> go under trees to keep dry in thunderstorms!
	4	No notice personal backcountry lightning risk reduction, including the 'lightning crouch' is no longer advocated for general audiences (Roeder, 2008), but it may be useful for groups that spend a lot of time outdoors away from safe places from lightning.
	5	<u>First Aid</u>: Immediately start cardiopulmonary resuscitation (CPR) or rescue breathing, as needed. Have someone call 9-1-1. Use an automated external defibrillator (AED) if available (do not delay CPR). Continue CPR/rescue breathing if AED won't activate.

Source: Roeder et al. (2012)

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[3] Lightning is the leading cause in of storm related deaths several coastal southeastern states. It accounts for ~1/2 of all storm related deaths in Florida.

[4] For example, at Level 5, in addition to an immediate 911/paramedic call, Roeder et al (2012) describe rescue breathing/cardio-pulmonary resuscitation and automated external defibrillator training as well as the promotion of understanding that those injured by lightning pose no shock threat to rescuers.

When workers are caught outdoors with a first strike, the “30-30 Rule” can be used to respond to a storm threat[5]. The delay between the lightning flash and the clap of thunder can be used to estimate how far away the lightning is from the work location. A 5-s delay means that the lightning is ~5,000 ft or ~1 mile away. Outside work should immediately stop and workers should hastily seek shelter for a minimum of 30 s (i.e., when the storm is ~6 miles away). An orderly shutdown and retreat to shelter can be implemented if the lightning to thunder interval is greater than 30 s when the presence of significant equipment or other risks of immediate cessation provide reasons to avoid a hasty retreat. Outdoor activities should not be resumed until 30 min after the storm has passed.

All facilities located in areas subject to thunderstorms and lightning should have a lightning safety plan that addresses the following considerations:

- The relative lightning density-by-time-of-year for the work location. Tropical and subtropical areas tend to have higher lightning risk (Cooper & Edlich, 2016) and thunderstorms are most common in Florida, on the Atlantic coast, and on the southeastern coast of the Gulf of Mexico.
- When storms are forecast, consider postponing outdoor work activities to avoid placing staff in dangerous situations, taking into account that lightning can strike 10–15 miles from an actual thunderstorm.
- Establish policies that direct workers to move promptly to the closest safe shelter when signs of a developing thunderstorm appear (e.g., darkening skies, thunder, or increased wind) and avoid open spaces, tall objects, and proximity to explosives or conductive materials such as metal (NWS, 2010).
- Safe shelters are most effective when they are fully enclosed buildings in which all wiring and plumbing are grounded (per Table 6.10-2, Level 2). During lightning storms, it is recommended to not touch, or stand near, corded phones, electrical equipment, wiring, and pipes.
- In the absence of a suitable safe shelter, a hard topped metal vehicle with all windows closed can provide some protection (IOSH, 2011).
- Delay resumption of outdoor activities until 30 min after the storm has passed.

Attention to local weather monitoring instruments and forecasting, as well as observation of developing weather conditions, can provide sufficient warning to suspend operations as lightning conducive conditions approach (Németh et al., 2007). Social media applications like Twitter and text alerts provide new, rapid methods for communicating warnings to workers scattered over a large area, but most remain to be formally implemented as warning systems.

Although meteorology warnings and public education have historically been the primary defense against injury or death by lightning, more recently active safety measures and weather/lightning monitoring instruments have come to the fore to mitigate lightning effects. For example, https://www.lightningmaps.org currently provides real-time, map-based updates for ground-based lightning detection. The GOES-R Geostationary Lightning Mapper is a satellite based lightning detector (see http://www.goes-r.gov./ GOES-R, 2016), which was launched in November 2016. Data from these types of sources can be used to determine whether storms

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[5] Lightning 30/30 rule: If it takes less than 30 s to hear thunder after seeing the flash, lightning is near enough to pose a threat; after the storm ends, wait 30 min before resuming outdoor activities (NWS, 2015).

moving toward NPPs are producing lightning, knowledge of which can be used to halt outdoor maintenance activities before lightning becomes a danger.

12.6 Interactions of Lightning with Other Environmental Conditions

The quick, intense flashes of light and loud sonic pulses that occur during lightning storms can cause both dazzle and startle effects and, if continuous, they can produce the same effects as prolonged aperiodic noise and disruptive flashes of light. Wind (e.g., intense downward and more rarely spawned tornadoes), precipitation (e.g., heavy rain and large hail), and standing and moving water from flash floods often accompany thunderstorms with a multitude of potentially adverse effects.

12.7 Summary of Research on Lightning Impacts

The state of research addressing the effects of lightning on performance demands is summarized in Table 12.2.

Table 12.2 Lightning effects on performance literature summary

Performance Demands	Applicable Levels of Information Related to Impacts	Assumptions and Limitations on Applicability
Detecting and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(a) (c)
Sensation and visual recognition	3	(a) (c)
Understanding		
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	3	(a) (c)
Decisionmaking		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(a) (c)
Action		
Fine motor skills – discrete and motor continuous, and manual dexterity	3	(a) (c)
Gross motor skills – heavy and light	3	(a) (c)
Other neurophysiological functions	3	(a)
Teamwork		
Reading and writing	4	(a) (c)
Oral face-to-face and electronic communication	3	(a) (c)
Cooperation, crew interaction, and command and control	4	(a) (c)

Assumptions and Limitations of Applicability

(a) The effects of lightning on performance demands cannot be ethically measured, because there is no safe level of lightning, but even indoors flashes and loud thunder can interfere with visual and aural tasks (see Chapter 6, Lighting, and Chapter4, Noise). When there is potential for lightning to occur, outdoor activities should be avoided completely.

(b) Electronic communication (e.g., telephones) can be completely disrupted by lightning. This may make communication between different groups of indoor or outdoor workers difficult, even if they are not experiencing lightning conditions.

(c) Thunderstorms typically last ~30 min (though sometimes several hours); consequently, outdoor activities can suffer from delays (and associated loss of continuity).

Level of Information Categories (1 to 4)

(1) Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance requirement and can be directly used to support the proof-of-concept approach.

(2) Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, personnel cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.

(3) Qualitative information. General agreement exists that the EC affects performance, but the measured impacts are not reported in the research literature, not even for limits. Performance may also be affected because an essential cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

(4) *No information (a gap).*

13 SUMMARY AND CRITIQUE OF THE RESEARCH LITERATURE

13.1 State of the Research Across Environmental Conditions

Table 13.1 summarizes the extent to which research supports the assessment of the effects on each of the performance demands for each of the 11 ECs, based on the opinion of the research team and their literature review. The rows in the table correspond to the performance demands and the columns correspond to the ECs. In each cell, the status of research is summarized on a scale of 1 to 4 reflecting descending levels of information as noted below the table (i.e., 1 denotes information directly applicable to quantitative impacts of an EC and 4 denotes an informational gap).

Table 13.1 reveals a mixed pattern of relevant research for the performance demands and ECs of interest. Broadly, the review found information with Level 1 quantitative impacts for only 8 out of 99 pairs (environmental condition by performance demands). On the other hand, only 27 cells are completely void of information useful for (1) informing a sensitivity analysis (Level 3) or (2) providing sufficient information for bounding effects regions (Level 2). Consequently, Table 13.1 represents an information basis that has considerable potential for conducting sensitivity, if not higher-level, analyses of the effects of ECs on MAs. An analysis of the impact of standing and moving water on a task requiring the individual to walk to and from a target destination illustrates the utility of this information (Prasad et al., 2017). However, focused research addressing the shortfalls in information about how ECs affect the performance demands represented in Table 13.1 is needed to realize the full potential of the impact assessment approach presented in this report and other assessment methods.

13.2 Opportunities for Future Research

There is opportunity for future productive research as indicated by recent conceptual and methodological advances (see Section 13.2) and the specific informational shortfalls identified in Table 13.1. However, this would require a focused, funded research program. Unfortunately, the literature search did not identify any large-scale ongoing or upcoming research programs that might produce these advances. It may be worthwhile to identify which EC-performance demand pairs present the most interesting and productive research topics.

This process could be both informed and accelerated by sensitivity analyses conducted in the process of modeling across case-specific manual actions (MAs). This process also could take advantage of the maturing research on stress, particularly discomfort, anxiety, and perceptions of risk that are relevant across ECs (see Chapters 2-12 of this volume). This research has reached a stage (especially regarding attention) where a series of studies could provide a basis for generalizations about impact on performance demands across ECs. Specifically, such research could involve mapping of the relationships between effects on performance demands and stress evoked by psychophysically matched EC exposures (Borg, 1988; Stevens, 1975). There is growing evidence that a common underlying mechanism across the ECs could be clarified and quantified (c.f., Lupien et al., 2007; Wessel & Aron, 2013). Indeed, matched modality loads may have similar patterns of impact across a spectrum of performance demands.

Direct estimation approaches (Borg, 1988; Stevens, 1975) offer a rapid, well-developed method for comparatively scaling the attentional loads for different ECs and/or combinations of ECs.[1]. This could provide a basis for establishing EC levels that represent equivalent attentional loads (i.e., matched modality loads). These EC levels could then be used to examine associated stress indicators/measures and impacts on performance demands, including teamwork studies, because individual stress levels could be used in a contemporary modeling approach (e.g., Edwards et al., 2014). Initially, research would be most productive if focused on a few selected ECs that are most pertinent for flood related planning. Confirmation research could then be conducted for all cross matched ECs. The Behavioral Evaluation for Epidemiology Studies Battery (Echeverria et al., 2002), selectively augmented with screener tasks (McCallum et al., 2005), would be a candidate for evaluating EC impacts across the spectrum of performance demands. This approach would be particularly productive, if it were conducted in the context of flooding concerns across a variety of process control settings (especially, NPPs). Activities in unsheltered settings would be of interest, but much could be learned regarding attentionally mediated performance demands in control room settings as well. Research structurally similar to that described in this section has previously proven productive in advancing environmental understandings across a spectrum of settings (Bittner, 1992; Bittner, Jr. et al., 1986; Harris et al., 1989; Lysaght et al., 1989; McCallum et al., 2005; Sanquist et al., 2012)

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[1] Bittner (2017) recently compared Direct and Borg RPE10 ratings of the felt recoil "aversiveness" for complex pulses delivered bimanually across four recoil levels in a single session (<3 hr). Log-direct and Borg-10 scales proved both highly reliable (r = 0.98 and 0.99, respectively), and inter-correlated (0.95) as well as strongly correlated with the log of the computed physical recoil (r = 0.98 and 0.93, respectively).

Table 13.1 Summary of extent to which research supports assessment of effects of environmental conditions on performance demands

Performance Demands	Heat	Cold	Noise	Vibration	Lighting	Humidity	Wind	Precipitation	Standing & moving water	Ice and snowpack	Lightning
Detecting and noticing											
Attention, memory, vigilance, switching, acuity, perception and threshold perception; Sensation and visual recognition	2	2,3	2,3	1,3,4	2,4	2,3,4	4	2,3	3	2	3
Understanding											
Pattern recognition, discrimination, evaluating, hypothesizing, diagnosing, and integrating	2,3, 4	4	4	3,4	2,4	4	4	3	3	3	3
Decision-making											
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3,4	2,3	1,3 ,4	3,4	2,4	4	4	3	3	3	3
Action											
Fine motor skills – discrete & motor continuous, manual dexterity	3	2	1,3	1	2	2	4	2	3	2,3	3
Gross motor skills – heavy and light	2	2	4	4	2	3	1	2	1	1,3	3
Other neurophysiological functions	2	3	4	4	2,4	4	4	3	3	4	3
Teamwork											
Reading and writing	4	3	1	2	2,4	4	4	2	3	2	4
In-person and electronic oral communication	2	4	2	3,4	2,4	4	3	4	3	3	3
Cooperation, crew interaction, and command and control	4	4	2,4	3,4	2,4	3	4	4	3	3	4
Research attention →	Extensive	Extensive	Extensive	Considerable, often does not address real world vibrations	Extensive	Mostly addressed as part of heat or cold	Limited literature, mostly on toppling	Limited literature, mostly on vehicle operation	Limited literature, mostly focused on gross motor effects	Very limited lit.	Very limited literature because of danger
Level of Information Categories (1 to 4) *1. Quantitative information that is directly applicable to determining the quantitative impact of an demand and can be directly used to support the proof-of-concept approach.* *2. Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available – below a lower limit, there is no discernible impact and above an upper limit, an individual cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide usable information.* *3. Qualitative information. General agreement exists that EC affects a performance demand, but measured impacts not reported in research literature, not even for limits. A performance demand may also be affected because a critical cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.* *4. No information (a gap).*											

14 GLOSSARY

acclimation – The process by which an individual organism adjusts to a change in its environment (such as a change in altitude, temperature, humidity, photoperiod, or pH), allowing it to maintain performance across a range of environmental conditions.

anticipatory action – actions completed in preparation for the occurrence of an event based upon the receipt of notification of the event due to the availability of warning time.

A-weighted decibel (dB(A)) – A weighted scale based on frequencies around 3,000 Hz to which the human ear is most sensitive that is often used when referring to the subjective loudness of noise.

catecholamines – Any of a class of aromatic amines that includes a number of neurotransmitters such as epinephrine and dopamine.

clothing thermal insulation index (Clo) – A measure of the insulating value of clothing. One Clo affords 13°F (~7°C) of protection from cold.

coefficient of friction (COF) – The ratio between the force necessary to move one surface horizontally over another and the pressure between the two surfaces.

color rendering index (CRI) – A scale from 0 to 100 percent indicating how accurate a given light source is at rendering color when compared to a reference light source. The higher the CRI, the better the color rendering ability.

contrast – In lighting, the ratio of the luminance of an object and the luminance of its background (e.g., how different the luminance of an object is from the luminance of its background).

decibel – The most common unit of measurement for the intensity of noise.

decomposition (of a manual action) – Analysis that deconstructs a manual action into tasks, subtasks (if necessary), and specific actions for the purpose of assessing the impact of environmental conditions on human performance.

design-basis flood – A flood caused by one or a combination of several hydrometeorological, geoseismic, or structural failure phenomena, which results in the most severe hazards to structures, systems, and components important to the safety of a nuclear power plant.

detection limit – The lowest quantity of a substance that can be distinguished from the absence of that substance (a blank value) within a stated confidence limit (generally 1%).

direct estimation method – Convergent method (psychophysics) broadly employed for directly scaling the magnitudes of a set of stimuli either (1) in terms of proportional numbers relative to each other or 2) by cross-modal matching to the magnitude of stimuli in another sensory or cognitive dimension.

dual task – A procedure in experimental (neuro)psychology that requires an individual to perform two tasks simultaneously, typically in order to compare performance with single task conditions.

duration – see flood event duration

effective temperature (index) – A single figure index reflecting the sensation of warmth that considers the combined effects of temperature, humidity, and wind.

environmental condition (EC) – The condition, due to an environmental phenomenon (e.g., from weather), that could exist during a flood of interest with a potential to affect human performance. Examples: heat (air temperature of 85°F), cold (air temperature of 30°F).

primary EC – An EC that does not require any other condition in order to affect performance. Examples: heat, cold.

secondary EC – An EC that would not occur without one or more primary ECs. Examples: slippery surface, mud.

environmental stressor – A stressor found in one's surroundings.

FLEX – Diverse and Flexible Coping Strategies.

flicker – The light-dark sequence created by very quickly switching a lighting source on and off.

flood event duration – "[t]he length of time in which the flood event affects the site, beginning with notification of an impending flood (e.g., a flood forecast or notification of dam failure), includes preparation for the flood and the period of inundation, and ending when water has receded from the site and the plant has reached a stable state that can be maintained indefinitely" (USNRC, 2012b, 2012d).

flood of interest – For the purpose of this report, a flood resulting from an event that would trigger initiation of flood protection or mitigation procedures at a nuclear power plant.

flood causing mechanism (FCM) – Flooding from a particular source, such as storm surge, dam failure, or local intense precipitation.

flood hazard – Conditions that facilities of a nuclear power plant may be exposed to during a flood event such as hydrostatic and hydrodynamic forces, debris accumulation, and impact forces that should be considered in the design to prevent loss of functionality.

flooding walkdown report – A report prepared by a nuclear power plant licensee to describe results of inspections to identify compliance with current design bases related to flooding.

flood protection and mitigation procedure – Any plant operating procedure (standard or abnormal) that implements external flood prevention, protection, or mitigation activities. For example, flood prevention activities (e.g., placement of sandbags or monitoring and clearing storm drains) are often contained in "adverse weather" or similar operating procedures.

generalized action (GA) – An individual component of a task or subtask that is sufficiently simple to evaluate the impact of ECs on human performance. GAs are general in nature, site-independent, and function as “building blocks” that can be used for recomposing or decomposing other manual actions.

glare – An intense or bright light that causes a reduction in visibility of a visual target.

hand-arm vibration syndrome – A painful and potentially disabling condition of the fingers, hands, and arms caused by exposure to vibration, initially indicated by a tingling sensation and numbness in the fingers.

Heat Index – An index that combines air temperature and relative humidity, in shaded areas, to determine the human perceived equivalent temperature, i.e., how hot it would feel if the humidity were some other value in the shade.

homeostatic mechanisms – Mechanisms that help regulate body heat to enable it to be in a steady state. The main mechanisms of homeostasis are body temperature, body fluid composition, blood sugar, gas concentrations, and blood pressure.

homeostasis – The tendency toward a relatively stable equilibrium between interdependent elements, especially as maintained by physiological processes.

human error – Any human action that exceeds some limit of acceptability, including inaction where required, excluding malevolent behavior. These include “slips” (e.g., pushing wrong button inadvertently), “lapses” (e.g., forgetting to add a recipe ingredient), and mistakes (not leaving enough room for a turn or understanding the consequences of an action).

human error probability (HEP) – A measure of the likelihood that plant personnel will fail to initiate the correct, required, or specified action or response in a given situation, or by commission performs the wrong action. The HEP is the probability of the human failure event.

human failure event (HFE) – A basic event that represents a failure or unavailability of a component, system, or function that is caused by human inaction, or an inappropriate action (ASME/ANS, 2009).

human reliability – The probability of successful performance of only those human activities necessary to make a system reliable or available.

human reliability analysis (HRA) – A structured approach used to identify potential human failure events and to systematically estimate the probability of those events using data, models, or expert judgment.

humidity – The amount of water vapor contained in a volume of air (usually expressed relative to the amount potentially contained, i.e., relative humidity).

hydrometeorological conditions – Characteristics including climate, terrain, soils, and proximity to waterbodies that influence floods at a location of interest.

hypothermia – The condition of having an abnormally low body temperature, typically one that is dangerously low.

Illuminance – The total luminous flux incident on a surface, per unit area; a measure of how much the incident light illuminates the surface, wavelength-weighted by the luminosity function to correlate with human brightness perception.

impact factor – A numerical measure of the increase in time to perform a specific action or the increase in error rate for performing a specific action.

inverted-U effects or relationships – A measure of performance relative to external effects. Performance increases with physiological or mental arousal, but only up to a point. When levels of arousal become too high, performance decreases. The process is often illustrated graphically as a bell-shaped curve that increases and then decreases with higher levels of arousal.

light intensity – The amount of energy emitted from a light source; the amount of illuminance from a light source.

luminance – A photometric measure of the luminous intensity per unit area of light traveling in a given direction; a description of the amount of light that passes through, is emitted by, or reflected from a particular area, and falls within a given solid angle. The SI unit for luminance is candela per square meter (cd/m^2).

manual action (MA) – For the purposes of this project, a distinct group of interrelated tasks that are performed outside the main control room to achieve an operational goal.

mechanism of action – the process through which an environmental condition has its effect on human physiology and/or cognition, and thereby human performance.

mental model – A person's internal, personalized, contextual understanding of how something works (i.e., a psychological representation of external reality) that is hypothesized to play a major role in cognition, reasoning, and decision-making.

Monte Carlo simulations approach – A method for estimating the distribution of outputs from a complex system using randomly sampled inputs to repeatedly perform system model simulations.

neurochemicals – Organic molecules, such as serotonin, dopamine, or nerve growth factor, that participate in neural activity.

neurophysiological functions – The functions of the human nervous system that are associated with coordinated physical and cognitive performances. Nerve conduction velocities, evoked potentials, and brain imagery represent some of the various measures of nervous system functions. These measures have been found to be adversely affected by exposure to environmental conditions (e.g., cold leading to hypothermia and slowing of nerve conduction velocities, cortical evoked potentials, as well as degradation of fine motor and gross motor performance).

noise – Unwanted, unpleasant, or annoying sound.

operator workload – Programmatic assessment of the extent to which the tasks performed by an individual use their limited processing resource (especially attentional, cognitive).

overtraining – Repetition of a skill until it tends to be largely performed automatically leaving the conscious mind available to focus on other things (also overlearning).

perception of risk – The subjective judgment people make about the characteristics and severity of a risk.

performance demand – The range of human physiological and cognitive abilities that are called upon to meet task requirements–performance degradation factor– Akin to a performance influencing factor or performance shaping factor, an aspect that serves to degrade the quality of human performance without specific reference to increasing or decreasing human error.

performance influencing factor (PIF) or performance shaping factor (PSF) – a factor that influences human performance and human error probabilities, including time available, stress/stressors, complexity, experience/training, procedures, ergonomics/human-machine interface, fitness for duty, and work processes (NUREG/CR-6883, Gertman et al., 2005)

permissible exposure limit – The legal limit in the United States for exposure of an employee to a chemical substance or physical agent.

phonological loop segment of working memory – The part of memory that deals with acoustic information such as speech and the interpretation of written words.

physiological collapse – Bodily collapse or near collapse with an inability to physically continue task performance.

probabilistic risk assessment (PRA) – A systematic method for assessing the likelihood of accidents and their potential consequences.

product number – The product of water velocity and depth that has been found experimentally to be strongly related to the probability of toppling a standing individual.

recommended alert limit – Heat stress alert limits recommended by the National Institute for Occupational Safety and Health for non-acclimatized workers.

recommended exposure limit – Heat exposure limits recommended by the National Institute for Occupational Safety and Health for acclimatized workers.

relative humidity – The amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature.

response time – The duration between the time a threshold for flood-response action is reached and the time the action must be completed.

reticular activating system – A set of connected nuclei in the human brainstem that is responsible for regulating wakefulness and sleep-wake transitions and serves in mediating attention and the “fight-or-flight” responses.

seiche – An oscillation of the water surface in an enclosed or semi-enclosed waterbody initiated by an external cause.

shear force – A force that acts along a surface (e.g., wind stress on a water surface) or unaligned forces causing a body to slide (e.g., pressure from water acting perpendicular to the vertical weight of a standing individual).

significance determination process (SDP) - The process used by the NRC staff to evaluate inspection findings to determine their safety significance.

slipperiness – The condition of surfaces or objects that are difficult to hold firmly or stand on because they are smooth, wet, or slimy; conditions that may cause a foot to slide and may result in injury or harmful loading of body tissues due to a sudden release of energy.

snowpack – Accumulated snow on the ground or other surfaces.

specific action (SA) – An individual component of a task or subtask, carried out in a site-specific task context, that is sufficiently simple to evaluate the impact of environmental conditions on human performance. SAs are site-specific and are obtained by decomposing site-specific manual actions.

sunny-day failure – dam failure due to non-hydrologic, non-seismic causes.

task – In the context of the decomposition of manual actions, one step of a manual action that has a distinct outcome or predetermined objective contributing to accomplishment of the manual action. A task is logically organized into cognitive and manual actions and generally requires both motor and cognitive abilities.

taxons – A taxonomic human performance category, especially as employed in the IMPRINT (Improved Performance Research Integration Tool) software.

taxonomy – A structured scheme of classification.

thermal balance – The state of a system at which inflowing and outgoing heat fluxes are in balance.

threshold flood response time – the duration between notification of impending flood or inundation/ponding and the time a threshold for flood response action is reached.

threshold limit value (TLV) – The level to which it is believed a worker can be exposed to a chemical substance day after day for a working lifetime without adverse effects.

toppling threshold – Conditions under which toppling of the human body is imminent.

tsunami – A series of water waves caused by the displacement of a large volume of a body of water, typically an ocean or a large lake.

turbidity – The cloudiness or haziness of a fluid; the relative clarity of a liquid.

VO_2 max – A measure of the maximum volume of oxygen that an athlete can use (usually measured in milliliters per kilogram of body weight per minute).

warning time – The time from when the event is known to present a threat to the plant (i.e., triggers) and the time when conditions could exceed permanently installed protections.

wetbulb globe temperature (WBGT) – A type of apparent temperature used to estimate the effect of temperature, humidity, wind speed (wind chill), and visible and infrared radiation (usually sunlight) on humans. It is a common measure of occupational heat stress.

wind chill index – The apparent temperature felt on the exposed human body owing to the combination of actual air temperature and wind speed.

vibration – An oscillating motion that serves to transfer mechanical energy.

visibility – The clearness with which objects can be seen; the relative ability to be seen under given conditions of distance, light, atmosphere, etc.

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10. SUPPLEMENTARY NOTES

M. Carr

11. ABSTRACT (200 words or less)

The U.S. Nuclear Regulatory Commission is carrying out a Probabilistic Flood Hazard Assessment Research Program to risk-inform external flood hazard assessment. One initiative is to better understand the actions that nuclear power plant licensees have planned to take outside of the main control room to prepare for, protect against, and mitigate the effects of external flooding events. The Pacific Northwest National Laboratory conducted a comprehensive review of research literature describing how the environmental conditions (ECs) associated with flooding events might affect performance of flood protection and mitigation actions. This report identifies and characterizes ECs associated with flooding events: heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning. The report identifies and characterizes a set of manual actions (MAs) that would be performed at and around NPP sites in preparation for or in response to a flooding event.

The report presents a conceptual framework that illustrates the relationships among ECs, MAs, and performance. The review of the research literature summarizes the state of knowledge concerning the effects of the ECs on human performance. The impact assessment approach is illustrated using a proof-of-concept method for an example MA.

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