INSTITUTE FOR DEFENSE ANALYSES

Path Analysis of Human Effects of Flashbang Grenades

Poornima Madhavan
Christian Dobbins

November 2018

IDA Document D-9270
Log: H 18-000393

INSTITUTE FOR DEFENSE ANALYSES
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

About This Publication

This work was conducted by the Institute for Defense Analyses (IDA) under contract HQ0034-14-D-0001, Project DU-2-4106, "Independent Research Assessments," for the Joint Non-Lethal Weapons Directorate (JNLWD). The views, opinions, and findings should not be construed as representing the official position of either the Department of Defense or the sponsoring organization.

For More Information

Poornima Madhavan, Project Leader
pmadhava@ida.org, 703-578-2822

Leonard J. Buckley, Director, Science and Technology Division
lbuckley@ida.org, 703-578-2800

Copyright Notice

INSTITUTE FOR DEFENSE ANALYSES

IDA Document D-9270

Path Analysis of Human Effects of Flashbang Grenades

Poornima Madhavan
Christian Dobbins

Executive Summary

The purpose of flashbang grenades is to elicit varying degrees of psychological and physiological distress from a human target while minimizing the risk of significant injury to the human. The Institute for Defense Analyses (IDA) was tasked with examining the interaction of physiological and psychological responses to flashbang grenades in order to understand the processes driving measurable performance outcomes after exposure to a flashbang. This report provides a detailed path analysis of human responses to flashbangs, their relationship with performance outcomes, and their implications for the design of human subject experiments to quantify these effects.

IDA used path analysis to identify what happens physiologically and psychologically between the deployment of a flashbang grenade and subsequent behavior change in the individual being subjected to the flashbang. Particular emphasis was placed on identifying relationships between immediate physiological effects such as eyeblink, intermediate psychophysiological effects such as distraction, and final measurable performance outcomes such as target detection and tracking accuracy, and targeting speed. The analyses were based on published studies of experiments with human subjects as well as those based on models of non-human organisms, mainly rodents.

Five immediate effects were identified as the starting point of the analyses—overpressure effects, hearing effects, the startle effect, StartReact (a cuing response that might enhance the performance of a planned motor action) and vision effects—each corresponding with unique physiological effects on the human body. For each immediate effect, we traced a path between the first physiological reaction and intermediate psychophysiological states such as distraction, disorientation and dizziness. The path from intermediate psychophysiological effects and final performance outcomes were then identified.

A major finding of our analyses is that negative shifts in affect, or emotion, play a critical role in moderating the relationship between the immediate physical effects of the flashbang and final performance outcomes by narrowing attentional focus and distracting attention away from pre-planned goals. Second, for the non-visually impaired population, the visual system tends to dominate other systems such as hearing, touch and taste/smell by suppressing or enhancing the sensitivity of other systems and weakening or strengthening other responses such as startle. The strong vision effects suggest that the “flash” component of flashbang may have greater immediate effect on humans than the “bang” component and requires further evaluation.

Implications of this report include ways to enhance the human effectiveness of flashbang grenades without raising the risk of significant injury. IDA recommends that future efforts at improving the effectiveness of flashbang grenades be focused on experimentally testing the variables and interactions identified by the path analyses presented in this report.

Contents

1. Introduction

A. Background

The typical flashbang grenade's explosive energy generates a deafening boom accompanied by a brilliant flash of light that can be temporarily blinding. Flashbangs have proven to be of low lethality over many years of tactical use but they can be either a lifesaver or a liability, depending on the manner in which they are deployed. Like all diversionary devices, the effectiveness and non-lethality of flashbangs are dependent on proper design, extensive laboratory and field testing, and training of users. There are three main components of a flashbang—the flash (or light), the bang (or sound), and the blast overpressure (or a sudden increase in air pressure). Flashbangs cause a range of human effects, both physiological and psychological, owing to a combination of these three components. During normal use, it is generally not possible to parse apart the effects of each component owing to complex interactions among them. The purpose of this report is to isolate the effects of each of the flashbang components and discuss them in the context of immediate effects of flashbangs, their causes and interactions, and their implications for measurable human performance outcomes.

B. Method

We conducted an in-depth literature review where we examined five immediate effects of flashbangs: (1) overpressure effects—the physiological and psychological effects of sudden increases in air pressure following the detonation of a flashbang; (2) hearing effects—the consequences of sudden loud bursts of sound characteristic of the "bang" component on the human neural and motor systems; (3) startle effect—the shock or "startle" element associated with flashbangs and the psychological and physiological distress that it might trigger; (4) StartReact—a potential improvement in the performance of planned motor movements; and (5) vision effects—the consequences of sudden blinding bursts of light characteristic of the "flash" component on the human oculomotor and other systems. We compiled research findings to identify the key cognitive and physiological variables that are affected in each of the five immediate effects. We then developed detailed path diagrams that illustrate the sequential steps in human responses starting with the deployment of a flashbang and ending with final performance outcomes (target detection, tracking accuracy and targeting speed) via intermediate psychological and physiological effects. We discuss two important variables that mediate and moderate the relationships among the five immediate effects and present two unified path diagrams in the last chapter that illustrate and highlight important connections between the effects and their implications for flashbang design and experimentation. The path diagrams presented in this report are original and were developed at IDA based on research findings published in the peer-reviewed literature.

2. Overpressure Effects

A blast is characterized by a sudden increase of air pressure (i.e., overpressure) followed by an almost immediate decrease in pressure and blast wind. In an open field, the energy of the blast waves decrease exponentially from the origin of the blast. However, indoors, blast waves rebounding off walls and rigid objects result in complex pressure waves which may enhance the original blast wave (DePalma et al. 2005). Particularly for the thorax, the traumatic loading of the chest wall by the blast causes a shock wave that propagates into the lung, and the pressure difference across the alveolar-capillary interface causes disruption, hemorrhage, pulmonary contusion, and subcutaneous emphysema. Pulmonary injuries may be life-threatening if extensive.

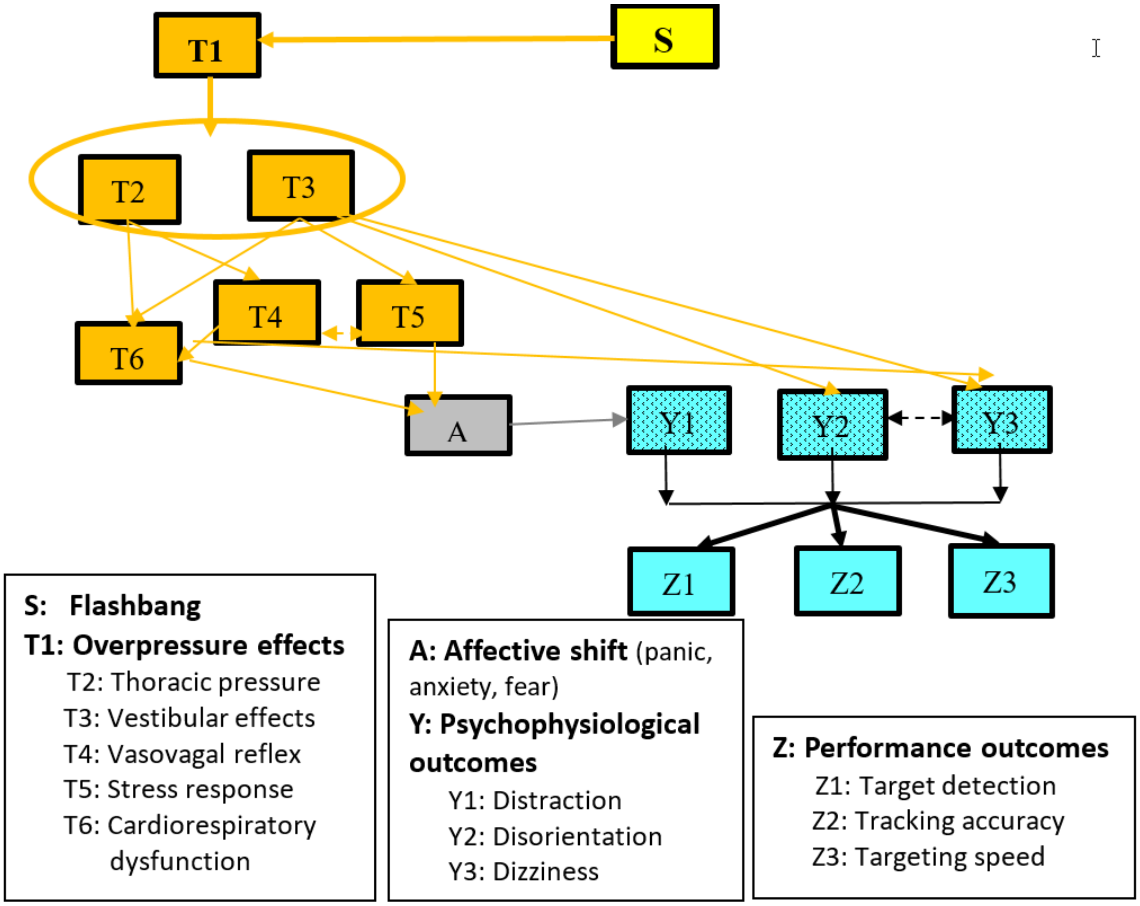


Figure 1. Effects of Blast Overpressure on Performance Outcomes

The effects of overpressure may travel through multiple pathways; some paths include direct passage of the blast wave through the skull, compression of the torso resulting in transfer of the blast wave's kinetic energy to the brain via hydraulic oscillations within the vasculature, and hypoxia through over-activation of the parasympathetic nervous system. As shown in Figure 1, effects of overpressure (**T1**) are parasympathetic or sympathetic. The parasympathetic response results from thoracic pressure (**T2**) and impacts to the vestibular system (**T3**) which is responsible for maintaining the body’s sense of balance and spatial orientation. Thoracic pressure leads to hyperinflation of the lungs and, together with vestibular effects, leads to cardiorespiratory dysfunction (**T6**) (Cernak and Noble-Haeusslein 2010, Krohn, Whitteridge, and Zukerman 1942; Zucker 1986; Zuckerman 1940). Cardiorespiratory dysfunction (**T6**) in turn can lead to palpitations and dizziness (**Y3**), and in extreme cases, loss of consciousness.

The vagus nerve has been shown to mediate autonomic responses to blast overpressure, which is represented as the “vasovagal reflex” (**T4**) in Figure 1. The vasovagal reflex, also triggered by increasing thoracic pressure (**T2**), is characterized by rapid breathing, bradycardia (slowing down of heart rate to less than 60 beats per minute), and hypotension (abnormally low blood pressure). The vagally mediated reflex has a significant role in traumatic shock. The vagus nerve can inhibit detrimental immune responses that contribute to organ damage in haemorrhagic shock; thus, the vasovagal reflex could inhibit systemic inflammatory responses to injury and prevent the development of shock, denoted as “stress response” (**T5**) in Figure 1. Stimulation of the vestibular system (**T3**) may also directly result in the activation of the sympathetic nervous system, which also influences the stress response (**T5**). Sudden surges in levels of physiological and psychological stress (or “shock”) in combination with cardiorespiratory strain (**T6**) trigger negative emotions such as anxiety, panic and fear, denoted by affective shift (**A**) in Figure 1, which, in turn leads to distraction (**Y1**). Simultaneously, overpressure effects on the vestibular system (**T3**) lead to disruptions in balance, movement, and spatial orientation leading to feelings of disorientation (**Y2**) and dizziness (**Y3**). Distraction (**Y1**), disorientation (**Y2**) and dizziness (**Y3**) exert measurable effects on performance by weakening the probability of target detection (**Z1**), the accuracy of target tracking (**Z2**) and the speed of responding to a target (**Z3**).

Modern day flashbangs can create pressure waves of nearly 30,000 PSI. Rodent models have revealed that exposure to medium-to high-level blasts (those above 30 PSI) triggered increases in respiratory rate, decreases in heart rate, atrioventricular blocks, and decreases in blood pressure, particularly when blasts were delivered exclusively to the rodents’ ear canals. These results are similar to those seen in whole-body and whole-head exposure paradigms, where the prevailing hypothesis is that these autonomic responses are due to lung injuries (Cernak and Noble-Haeusslein 2010, Zucker 1986, Zuckerman 1940).

It must be noted that the majority of overpressure effects, and in particular, hypotension, are only elicited by blasts of 30 PSI and above.

3. Hearing Effects

Scientific literature has documented reliable effects of acoustic noise on visual monitoring efficiency and subsequent task performance. In some cases, sound is found to impair performance and in others to improve it. There are two principal variables which might conceivably differentiate between facilitatory and inhibitory effects: characteristics of the sound and its source, and characteristics of the task and environment. Because the human ear does not have equal sensitivity to stimuli over the entire frequency and sound pressure ranges, the dB scale does not entirely equate to what an observer perceives. The apparent subjective loudness of a stimulus is therefore a function not just of the intensity but also of the duration, variation of intensity, and frequency of the sound waves (Szalma and Hancock 2011). The intensity and duration of exposure have been the primary foci of research on noise effects in human perception and performance.

One of the most disturbing forms of noise on humans is that of intermittent noise; some examples are sounds that rise and fall in wavelike patterns (e.g., emergency vehicle sirens) or sounds that are interspersed among other sounds (e.g., drumbeats in music). The source of performance perturbation in such situations is posited to be the distraction of attention away from the task and to the source of the noise (Szalma and Hancock 2011). When the intermittent noise (noise range 1–2 seconds) occurs at high intensities, the individual briefly diverts his or her attention to the noise in the form of an orienting response. Such responses are maximized under so-called impact noise, that is, relatively infrequent and short duration bursts of noise (Casali and Robinson 1999). Intermittent and/or sudden bursts of noise tend to be more disruptive than continuous noise; however, researchers argue that it is the sudden change in intensity of noise rather than the intermittency or suddenness per se that is responsible for performance effects (Loeb 1986). We discuss the immediate effects of one sudden loud burst of noise from a flashbang in the subsections below. The focus of this section is on hearing effects alone and not the accompanying startle effect, which will be discussed in a separate section.

A. Aural Pain

Impulse noises, when loud enough, can produce significant physiological effects associated with pain. Flashbang grenades generate noise levels far above those considered comfortable for the human ear, and even a brief stimulus duration is enough to cause great discomfort if not permanent damage (Robertson 2005). While hearing discomfort can occur around the 110 dB mark, the typical threshold for aural pain sits around 120–140 dB (Licklider and Miller 1951). A flashbang can generate a loud bang of greater than 170 dB.

As illustrated in Figure 2, when the perceived magnitude of the auditory stimulus (in this case, the "bang") reaches or exceeds the acceptable pain threshold, signals traveling from the cochlear pathway to higher centers of the brain prompt a stress response very similar to that triggered by ocular pain from intense light stimuli (discussed in a later chapter). This experienced aural pain is denoted by **U2** in Figure 2. Pain demands attention; therefore, in addition to the immediate stress response (**T5**) from experienced pain and resultant negative shift in affect (denoted by "affective shift" **A**), a more direct impact on performance through distraction (**Y1**) should occur (Linton and Shaw 2011). Distraction results in impaired ability to detect (**Z1**) and track targets (**Z2**) and increased time to react (**Z3**) once targets are detected.

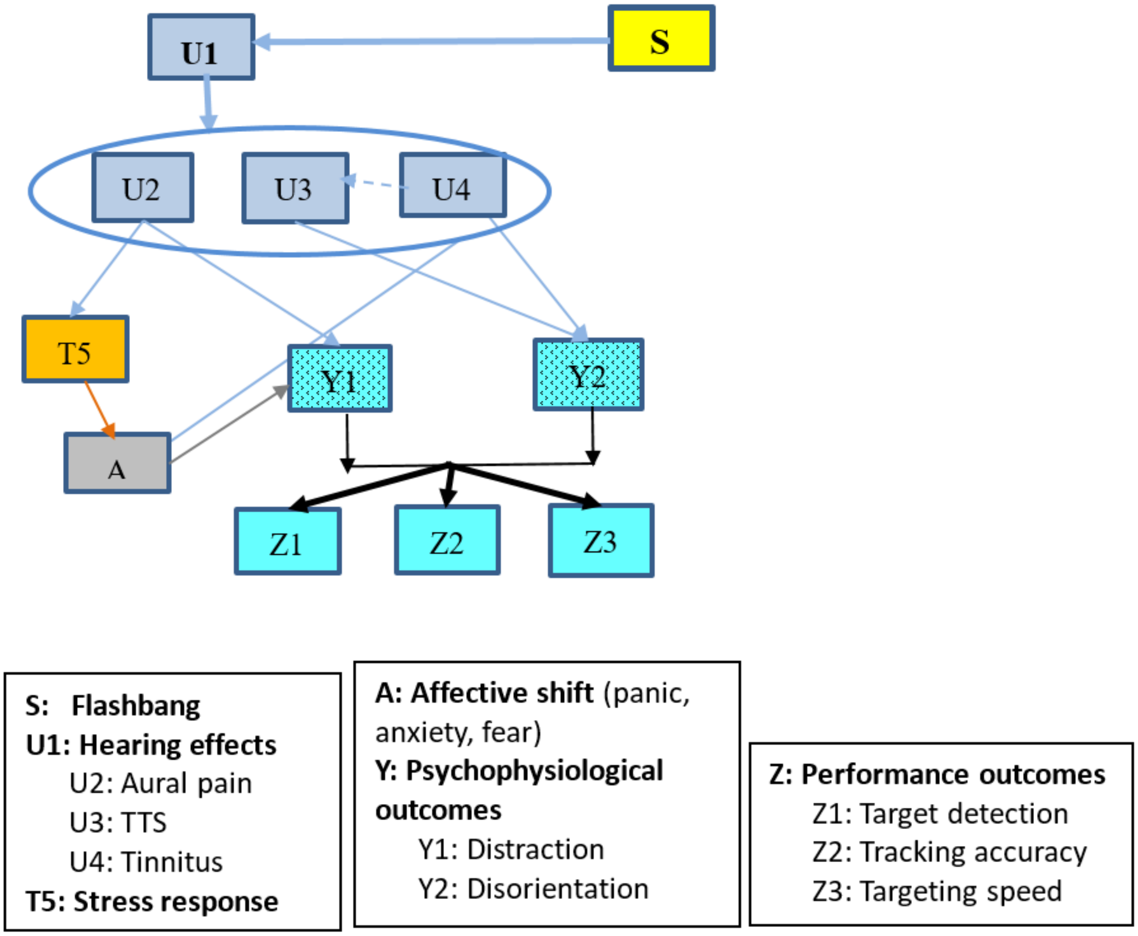


Figure 2. Effects of Flashbang Exposure on Hearing and Subsequent Performance Outcomes

B. Temporary Threshold Shift

Blast exposure substantially raises the risk for temporary and permanent hearing loss in humans. A temporary threshold shift (TTS) is a temporary shift in the auditory threshold that may occur suddenly after exposure to a high level of noise, a situation in which most people experience reduced hearing. TTS is denoted as **U3** in Figure 2. TTS results in temporary hearing loss and is often accompanied by tinnitus. TTS is normally caused by exposure to intense or loud sounds and is relatively independent of exposure duration. It may result from exposure to loud noise for short durations (such as an explosion) or for longer durations (such as a concert). TTS tends to be maximal at the exposure frequency of the sound. Full recovery from TTS can be achieved in approximately 2 minutes for blast exposure, depending on the severity of the TTS. Also, it is possible for TTS to get worse in the first 30 minutes or so after exposure before recovery occurs. As can be seen in Figure 2, TTS (**U3**) leads to a temporary state of disorientation (**Y2**) due to a temporary disruption in hearing ability, or "deafness." As mentioned in the earlier subsection, disorientation slows down response time (or, targeting speed; **Z3**) and weakens the ability to detect (**Z1**) and track a target (**Z2**).

C. Tinnitus

Tinnitus is the prolonged perception of noise or ringing in the ears and is typically a symptom of an underlying condition, such as an ear injury or a circulatory system disorder; it is characterized by the sensation of hearing sound when no external sound is present. Tinnitus symptoms include the perception of phantom noises in the ear such as ringing, buzzing, roaring, clicking or hissing. The phantom noise may vary in pitch from a low roar to a high squeal, in one or both ears, and may be continuous or intermittent. As can be seen in Figure 2, tinnitus (U4) is one of the immediate hearing effects of a flashbang device. Among the different noise sensations, exposure to a flashbang is most likely to result in a high-pitched ringing or buzzing sound in the ear that may last as long as a few hours. Since tinnitus can manifest itself in different ways, each individual's experience is unique. Although some people are relatively unbothered by tinnitus, others may experience significant negative affect (A) such as anxiety, nervousness and irritability due to an increase in activity in the amygdala. In addition, research in neuroscience has found changes in frontal lobe activity for people experiencing tinnitus (Carpenter-Thompson et al. 2015). This is notable because the frontal lobe is typically used for tasks that require attention, planning and impulse control. Frontal lobe damage has been associated with feelings of disorientation (Y2) and impaired ability to plan and execute action.

As shown in Figure 2, the consequences of tinnitus can be twofold. First, tinnitus may immediately trigger a state of negative affect (A) via the amygdala; situational surges in negative emotion have been associated with distraction (Y1) leading to a slowing down of reaction time (Z3) and the loss of ability to locate (Z1) and track a target (Z2). For example, in the domain of driving, negative emotional cues have led to drivers drifting and veering from lanes, while slowing their rate of braking (Chan and Singhal 2015). Second, tinnitus may disrupt attention and the ability to plan and execute action via frontal lobe activity, triggering a state of confusion and disorientation (Y2). Disorientation, in turn, slows down targeting speed (Z3) and weakens the ability to detect (Z1) and track a target (Z2). Specifically, aiming and shooting behaviors can be delayed by 1 to 2.5 seconds in response to loud bursts of 110, 120 and 130dB (Tikuisis et al. 2009).

4. Startle Effect

The shock or “startle” element associated with flashbangs can trigger varying degrees of psychological and physiological distress. Arguably, the “startle” alone may result in more serious consequences (e.g., stress to vital organs such as the heart) than the physical effects of the flashbang per se. In humans, the startle response is most commonly elicited by auditory stimuli, although visual (McManis Bradley et al. 2001), somatosensory (Gokin and Karpukhina 1985) and vestibular stimuli (Bisdorff, Bronstein, and Gresty 1994) have also been known to produce the effect. The startle response, typically a response to unexpected stimuli, is the consequence of involuntary activation of the motor tracts that is generated in the brainstem, and is the fastest known generalized motor reaction of humans and animals.

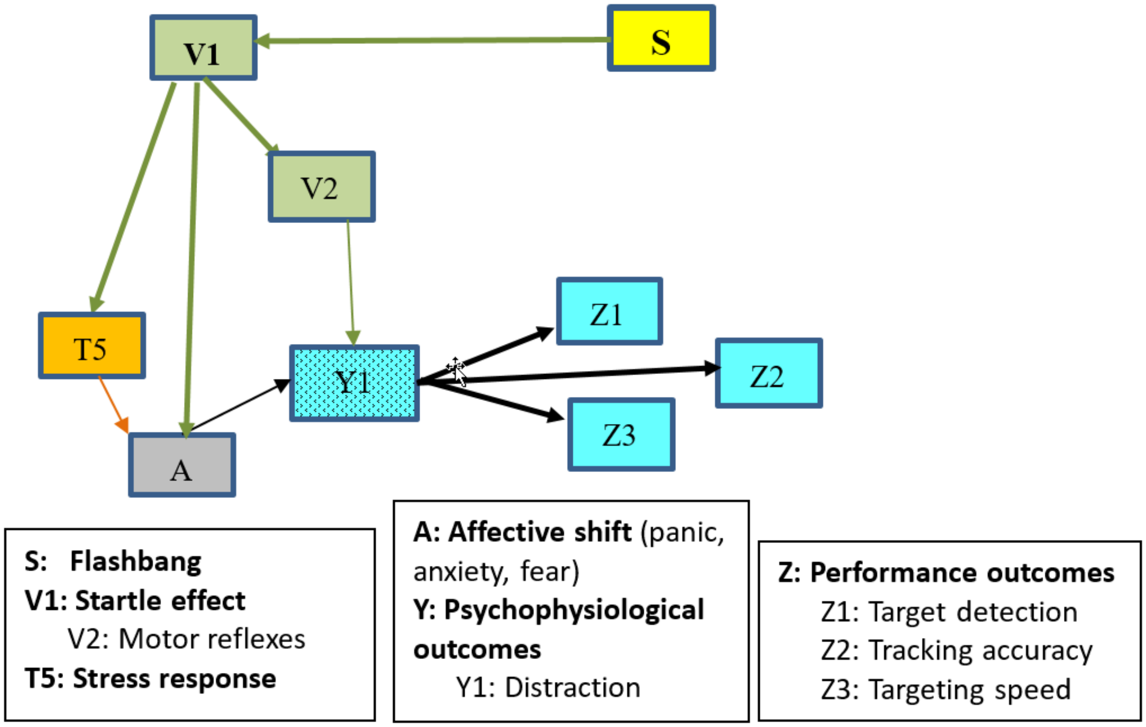


Figure 3. Effects of Flashbang Exposure on the Startle Effect and Subsequent Performance Outcomes

As can be seen in Figure 3, the startle response (**V1**) typically leads to a motor reflex (**V2**) that comprises an early brief and generalized muscle contraction lasting a few milliseconds. Specifically, this motor reflex is characterized by rapid activation of the facial and skeletal muscles, leading to a whole body flinch within a few milliseconds. This is followed by a more elaborate motor activity, such as turning of the head in the direction of the stimulus, resulting from the central integration of all sensory information conveyed by the stimulus.The startle motor reflex leads to distraction (**Y1**) that in turn weakens the ability to detect (**Z1**) and accurately track a target (**Z2**), and significantly slows down targeting speed (**Z3**). Startle also leads to an increase in negative affect (denoted by "affective shift" **A** in Figure 3) wherein feelings of panic, fear and anxiety are spontaneously triggered as a result of the stress (**T5**) generated by a startle-eliciting stimulus. As noted in previous sections, a negative shift in affect creates a state of distraction (**Y1**) which, in turn, leads to impaired performance outcomes (**Z1, Z2, Z3**).

Motor reflexes have been found to be impaired significantly in the 2 seconds immediately following exposure to the startling stimulus but not thereafter. Specifically, studies have shown that motor performance following startle is disrupted for approximately 0.1 second to 3 seconds for simple tasks such a pressing a key (Rivera et al. 2014). The normal reaction time for such simple tasks ranges from 0.1 seconds to 1.6 seconds. In more complex motor tasks, such as continuous target tracking, startle may impact performance for up to 10 seconds following a loud sound. Although simple responses like target monitoring might recover relatively quickly (in approximately 2 seconds) upon removal of the startle eliciting stimulus, startle has been found to impair higher level information processing such as problem solving and decision making for as long as 30 seconds to 60 seconds after the startling stimulus has been removed.

The startle effect is also associated with the eyeblink reflex, which is also known as the blink reflex or corneal reflex. This reflex is represented by an involuntary blinking of the eyelids, elicited by stimulation of the cornea (such as by a bright light). In most cases, the blink is caused by direct stimulation, although in some cases the blink might result from peripheral stimulation. Pupil constrictions and dilations regulate the amount of light entering the eye and pupil dilation begins as early as 0.7 seconds before the initiation of a motor response (Hupé, Lamirel, and Lorenceau 2009). Stimulation with sudden light flashes could elicit both a direct response (response from the stimulated eye) as well as a consensual response (response from the opposite eye). The eyeblink reflex follows at a rapid rate of 0.1 second and its evolutionary purpose is to protect the eye from foreign bodies and bright lights. The blink reflex also occurs when sounds greater than 40-60db are made (Garde and Cowey 2000). Eyeblinks may also engage the acoustic reflex, which is a middle-ear contraction that protects the auditory system, suggesting the cross-modal coupling of eyeblink responses. The use of contact lenses may diminish or abolish the eyeblink reflex.

In general, increases in stimulus intensity (i.e., loudness, brightness) tend to elicit startle responses of greater magnitude, amplitude, and probability, with shorter onset latency (Reynolds 2012). A startle response can be elicited with acoustic stimuli as low as

50 dB; however, some research shows that the probability of eliciting a response might drop below 50% around 85 dB. For this reason, it is recommended that acoustic stimuli be approximately 100 dB for maximal effectiveness (Blumenthal et al. 2005). This level of sound produces consistent startle responses while minimizing risk of significant injury. Unlike acoustic stimuli, there is no agreed-upon degree of brightness (of a visual stimulus) that might elicit a startle response. However, a synthesis of research indicates that whereas the effective sound level required for a single impulse noise to startle differs very little from that which is considered to be harmful to hearing, the flash intensity required to produce a similar effect might be more than an order of magnitude lower than the level causing vision damage (Valls-Solé et al. 1995; Odgaard, Arieh, and Marks 2004; VanMeenen et al. 2006).

Rise time, or the amount of time it takes for the stimulus to reach full intensity, is another important consideration as a startle stimulus parameter, since the startle reflex is sensitive to sudden, transient changes in the environment (Graham 1978). Stimuli with short or instantaneous rise times lead to startle responses of greater magnitude, probability, and amplitude, with shorter onset latencies when compared with stimuli with longer rise times. Stimuli with longer durations also tend to elicit startle responses with greater probability and magnitude until the effect reaches asymptote at 0.5 seconds (Blumenthal and Berg 1986).Therefore, the most commonly used duration for startle eliciting acoustic stimuli is about 0.5 seconds.

5. StartReact

Unlike the performance impairments resulting from the startle effect discussed in the previous section, under some circumstances early preparation for a specific motor action can actually benefit from the appearance of a startling stimulus. As can be seen in Figure 4, in the StartReact effect (**W1**) a startling acoustic stimulus may actually lead to faster execution of certain planned motor movements (**W2, Z3**) such as punching, throwing and striking by .2 to .5 seconds (Valls-Sole et al. 1995). An example of the StartReact effect is the response of athletes to the starter pistol during a race. This happens due to the stimulus enhancing the excitability of some neural structures used for driving voluntary motor responses.

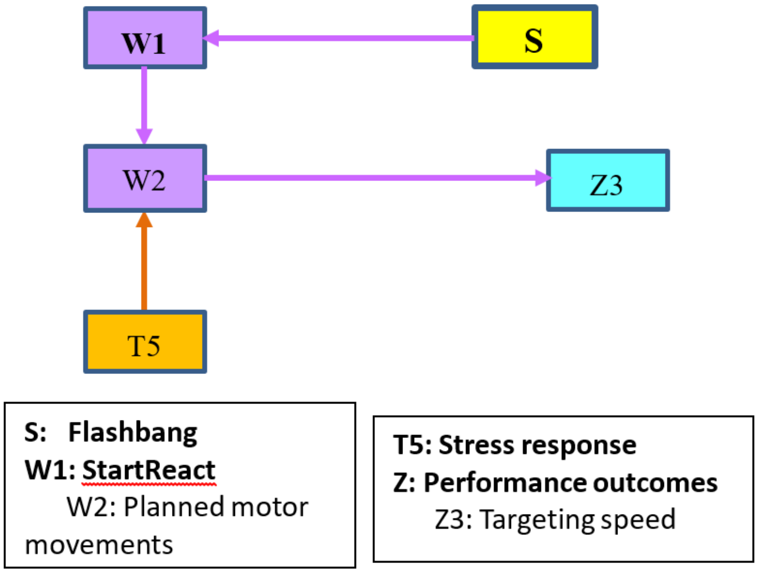


Figure 4. Effects of Flashbang Exposure on StartReact and Subsequent Performance Outcomes

Studies using auditory stimuli have found that an overt startle response is not necessary for the StartReact effect to be observed (Reynolds 2012). There are similarities between the StartReact effect and another cognitive phenomenon known as the Accessory Stimulus Effect, in which a practiced reaction to a target stimulus becomes faster if the target stimulus is paired with an unrelated stimuli from a different modality (Hackley and Valle-Inclan 1998, Jepma et al. 2009). For example, a planned response such as shooting a target might momentarily speed up if the target appears in conjunction with a sudden unexpected sound. For both StartReact and the Accessory Stimulus Effect, inter-sensory facilitation seems to play an important part in the execution of a planned motor action. Other than the planned motor movements mentioned above, StartReact can have an effect on more complex automatic movements like walking (Schepens and Delwaide 1995; Nieuwenhuijzen et al. 2000), gait initiation (MacKinnon et al. 2007), sit-to-stand actions, and obstacle avoidance (Queralt et al. 2008).

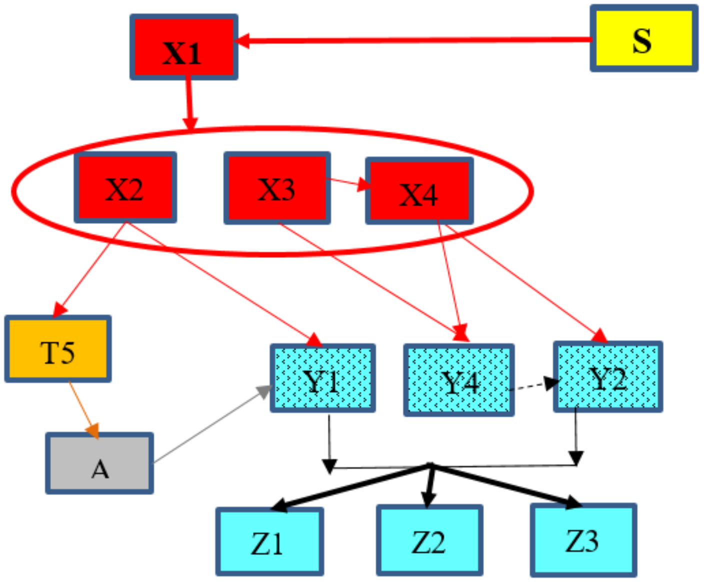
The performance improvements seen via StartReact may also interface with the activation of the sympathetic nervous system, or the stress response (**T5** in Figure 4). When the body is subjected to stress, the endocrinal effects of epinephrine and norepinephrine released from the adrenal gland lead to changes in blood, oxygen, and glucose levels which are associated with salient improvements in muscle tone. Individuals experiencing an acute stress response may be able to move more quickly, contract muscles more strongly, and may tire less quickly (Krahenbuhl, 1975). It must be noted that although immediate movements may be facilitated by StartReact (Wegner, Koedijker, and Budde 2014), the dose-response curve is bell-shaped, with over-arousal leading to eventual performance decrements. Another important observation is that the other stress reactions discussed in this report are consequences of the visual/auditory stimulus, whereas with StartReact stress is an antecedent condition. That is, the path direction is reversed.

6. Vision Effects

One of the most prominent characteristics of a flashbang grenade is the “flash”—a brief but brilliant display of light that is intended to be immediately blinding to the observer The “flash-effect” is a temporary and reversible reduction in the ability of an individual to respond to a visually oriented task following a brief exposure to an abrupt increase in the brightness of all or part of the field of view; this state can be likened to a state of visual overload. Studies indicate multiples changes in the human oculomotor system as a function of light exposure. White light, commonly in the form of sunlight and incandescent light, encompasses all wavelengths of the visible spectrum; variations of green light, often used in traffic lights, non-lethal stunning devices, and industrial controls and indicators, cover approximately 1/15th of this spectrum. Light of green wavelength (520 nm) reportedly results in the longest readaptation time after exposure (Wang, Goldman and Tengroth 1990). This suggests that even though green light comprises only a portion of the optical spectrum, it may have more intense effects on human behavior than white light (Chua et al. 2004). In the sub-sections below we discuss specific cognitive and behavioral effects of light flashes, their immediate effects on human physiology, and their implications for subsequent task performance, mainly target tracking, targeting accuracy and reaction time.

A. Ocular Pain

Human subjects display discomfort in response to sudden, intense light. These responses can include squinting, blinking, wincing, or averting gaze (Stringham, Fuld, and Wenzel 2003). As illustrated in Figure 5, the first vision effect (**X1**) of flashbangs is ocular pain (**X2**). Also known as discomfort glare, ocular pain is proportionate to the intensity of the light over a comfortable threshold and the reason for this experienced pain can be understood when considering the function of the oculomotor system. The purpose of this system, and the retina in particular, is to provide resolution of objects in the visual field and the environment (Stone 2009). When contrast detection is hindered, compensatory processes engage to enhance our vision with light adaption mechanisms. One example is the pupil changing size in response to the amount of light entering the eye. This is generally a balancing act between the competing demands of sensitivity and resolution. If some area of the visual field receives luminance that is disparate from the ambient luminance level, adaptation becomes difficult and discomfort is experienced (Howarth et al. 1993). Ocular pain is a signal that damage is imminent or occurring. Bright light can damage the neural tissue of the retina and other ocular structures, so the rapid removal of noxious stimuli is imperative to minimize negative impacts on the visual system.



S: Flashbang
X1: Vision effects
X2: Ocular pain
X3: Bleached photopigments
X4: Afterimage
T5: Stress response

A: Affective shift (panic, anxiety, fear)
Y: Psychophysiological outcomes
Y1: Distraction
Y2: Disorientation
Y4: Flash blindness

Z: Performance outcomes
Z1: Target detection
Z2: Tracking accuracy
Z3: Targeting speed

Figure 5. Effects of Flashbang Exposure on Vision Effects and Subsequent Performance Outcomes

Neurophysiological changes follow the introduction of intense light to the non-adapted eye. The iris contains muscles which dilate or constrict the pupil adjusting its size, referred to as the iridomotor system (Howarth et al., 1993). The upward movement of these signals to higher areas of the brain takes multiple routes and is of interest when considering the psychological implications of memory, emotion, and pain (Stone 2009). The impending tissue damage signaled by ocular pain triggers a stress (or shock) response (**T5**) to optimize chances of escaping or eliminating the given threat and creates a state of negative affect (**A**). Simultaneously, there is a more direct impact on performance outcomes by way of distraction. The momentary distraction caused by physical pain to the eye leads to impaired ability to visually detect (**Z1**) and track targets (**Z2**) and slows down speed of targeting (**Z3**).

Research has demonstrated that an increase in the luminance of the stimulus causes higher levels of reported pain. In experimental settings, exposing subjects to pre-test luminance to allow some degree of light adaptation or habituation reduces discomfort. If the flash size is increased but the luminance is held constant, reported pain increases.

Likewise, if the light stimulus is experienced closer to the center of the field of vision instead of peripherally, discomfort is reportedly greater. Overall, there is a great deal of variability in the ocular pain thresholds among people (Waters, Mistrick, and Bernecker 1995).

B. Bleached Photopigments

Exposure to sudden brilliant light triggers the process of light adaptation in the human eye wherein the retinal pigment rhodopsin absorbs the light energy. Bleaching of photopigments (**X3** in Figure 5) limits the degree to which the rods are stimulated, decreasing their sensitivity to bright light. This leads to a temporary state called "flash blindness" (**Y4**)—a reversible change in the adaptational state of the eye to a sudden increase in the ambient illumination. During this temporary state of blindness, virtually nothing is visible except a positive or negative afterimage (**X4**). The effects of flash blindness on human behavior differ based on the type of task being performed, the amount of light stimulation, and the contrast between the types of light in reference and existing ambient light.

There are numerous sensory-level parameters that can alter the effect of light flashes on the human visual system. Ocular parameters include pupil size, adaptational state, age of the individual, and location and size of the flash on the retina. Important features of the stimulus include the energy incident on the retina, duration of the flash, light wavelengths, and number and frequency of flashes (VanMeenen et al. 2006). Task demand parameters can also influence the effectiveness of sensory interference; the size and level of luminance and visual contrast are important variables. Research has revealed that light interference that leads to flash blindness can delay targeting speed (**Z3**) by about 0.9 seconds and disrupt detection of targets (**Z1**) and ability to track targets (**Z2**); in cases where sound accompanies flash, sound interference may delay targeting responses by an additional 0.4 seconds, although sound has been found to exert no direct influence on targeting accuracy (VanMeenen et al. 2006). The light interference effects on targeting latency and accuracy increase proportionally with increases in flash intensity and unpredictability.

C. Afterimage

One of the causes of the blinding effect described above is the afterimage (**X4**) in Figure 5) created by the flash on the retina. An afterimage is a visual phenomenon in which some features of an image persist even after the visual stimulus ceases. Specifically, after a flash of bright light, cells within the light-exposed area of the retina become less sensitive to light compared to those outside that area, so they subsequently fail to respond appropriately to normal levels of light (Chua et al. 2003). Exposure to bright light can produce an afterimage lasting for minutes to hours to days depending on the intensity and duration of the source light. Afterimages caused by expedient lights such as flashlights and sudden flares from flashbangs has been shown to provoke spatial disorientation (**Y2**) for varying lengths of time (Schmidt 1999). Afterimages have practical applications in law enforcement and military operations in terms of stunning opposing forces without causing long-term physical or cognitive damage.

The appearance of an afterimage causes competition for visual attention and has immediate effects on the dynamics of the saccadic oculomotor system. Research has revealed that photic stimulation following flashes of light leads to latencies in saccadic eye movements (Chua et al. 2003). Specifically, eye movements have been found to be visibly slower following the appearance of a flash-induced afterimage, leading to a general slowing down of decision speed (**Z3**) and weakening of target detection (**Z1**) and tracking accuracy (**Z2**). Although there is variability in the extent to which flash location (relative to the observer) leads to disorientation, there is some consensus that flashes located 15 degrees to the left of the observer lead to the most significant slowing down of eye movements leading to subsequent attention disruption (Chua et al. 2003).

7. Mediating and Moderating Variables

In general terms, a moderator is a qualitative (e.g., age, gender) or quantitative (e.g., level of reward) variable that affects the direction and/or strength of the relation between an independent or predictor variable and a dependent or criterion variable (Baron and Kenny 1986). Specifically within a correlational analysis framework, a moderator is a third variable that affects the zero-order correlation between two variables or influences the strength of the relationship between the two variables. In our flashbang pathway model, a moderator would be a variable such as affective shift (change in emotional state) that plays a role in the extent to which other variables such as cardiorespiratory dysfunction or startle influence psychophysiological outcomes.

A given variable may be said to function as a mediator to the extent that it accounts for the relation between the predictor and the criterion (Baron and Kenny 1986). Mediators explain how external physical events take on internal psychological significance and provides an explanation for the relationship between two other variables. Whereas moderator variables specify when certain effects will hold, mediators explain how or why such effects occur. In our flashbang pathway model, orienting and defensive reflexes would serve as mediating variables that determine immediate effects on all other variables. These variables are explained in the sub-sections below.

A. Orienting and Defensive Reflex

The orienting reflex, also known as the “what-is-it?” reaction or the “investigatory reflex” is a reflex that is essential for survival. It is an important mechanism for attention to novelty and alerts us to changes in our sensory environment by directing the individual’s attention toward the source of stimulation. Once the orienting reflex is elicited, the individual may decide whether and how to act upon the stimulus. Orienting reflexes are easy to habituate and may disappear entirely after repeated presentations of a stimulus.

The orienting reflex is not always associated with investigatory behavior, but may be related to reactive involuntary attention to changes in stimulation (Sokolov 1963). This may range from a reaction to a sound to an abrupt presentation of light such as a flash. The orienting reflex functionally “tunes” the appropriate receptor system to ensure optimal conditions for perception of the stimulus. For example, a person may blink their eyes in response to a change in illumination, jerk their head in response to a startling sensation, or their ears may prick up in reaction to a new sound. When the orienting reflex is elicited in one sensory system (e.g., vision), activity is slowed down or halted in other sensory systems, thus allowing the individual to prepare for necessary action in the primary sensory system (Sokolov 1963). If the stimulation is intense, the nervous system seeks to dampen the stimulus' intensity via the defensive reflex.

The aim of the orienting reflex is to increase receptor sensitivity; however, if the stimulus reaches the critical level of intensity associated with pain or other negative impacts, the defensive reflex develops. The defensive reflex can be considered the converse of the orienting reflex. Just as the orienting reflex serves to enhance the perception of the stimulus, the defensive reflex raises perceptual thresholds to keep the impact of the stimulus within perceptually tolerable boundaries. They differ in their ultimate objective: the orienting reflex brings the organism in contact with the stimulus, the defensive reflex limits the impact of the stimulus on the organism. Similar to the orienting reflex, the defensive reflex is a generalized reaction and is not limited to any specific sensory system.

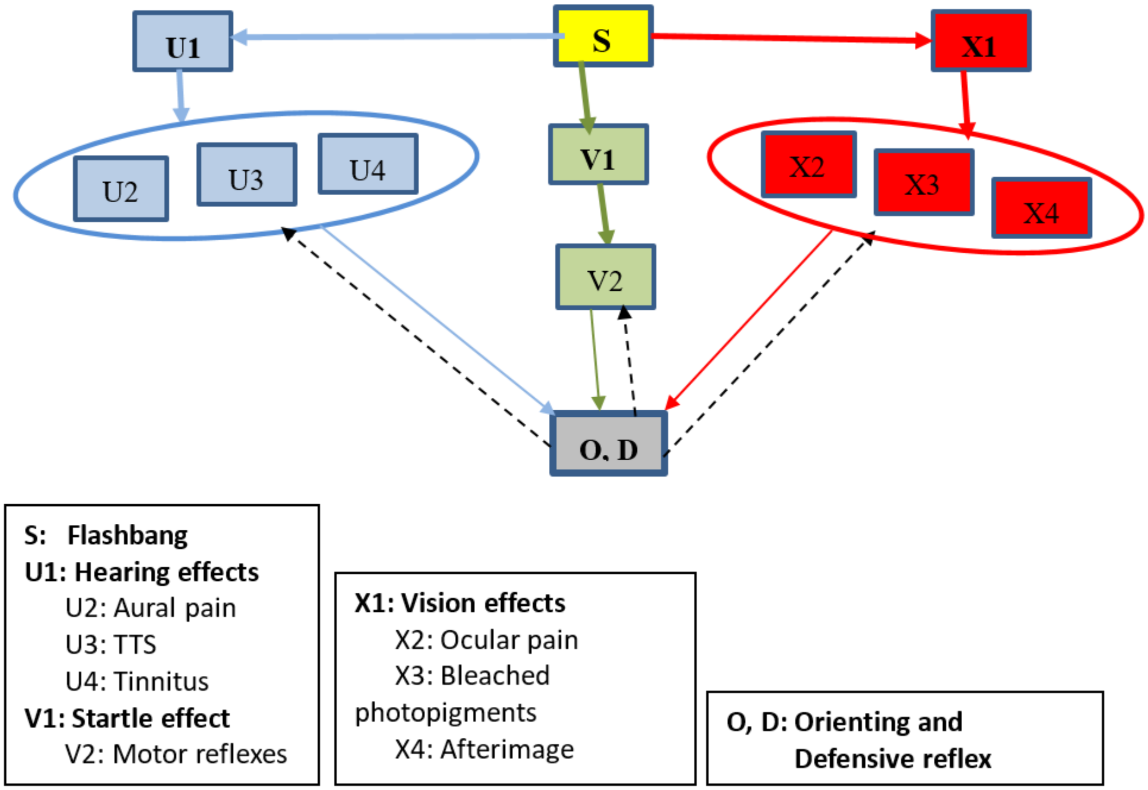


Figure 6. Orienting and Defensive Reflexes

The orienting and defensive reflexes have both behavioral and physiological components (e.g., heart rate change, head turning, EEG activation) that occur in response to the introduction of a novel stimulus. The primary behavioral component is the "orientation" of the receptor organs of the primary senses toward the source of stimulation or the "defending" or "turning away" of the receptor organs from the source of stimulation. The mediating role played by the orienting and defensive reflexes in the context of a flashbang is illustrated in Figure 6, where the orienting reflex is denoted by “**O**” and the defensive reflex is denoted by “**D**” in the box “**O, D”**. In the context of hearing effects (U1), aural pain, TTS or tinnitus (or some combination of them) will lead to an increase in sensitivity to sound. However, this increase in sound sensitivity will lead to a simultaneous decrease in sensitivity to light and startle (denoted by the dotted arrow going from **O, D** to **X2, X3, X4** and **V2**). In the context of startle (**V1**), the motor reflexes triggered would lead an individual to perform orienting movements such as a head tilt in the direction of the stimulus. This would lead to a simultaneous weakening of responses to sound and light (denoted by the dotted arrow going from **O, D** to **U2, U3, U4** and **X2, X3, X4**). Similar to hearing and startle effects, in the context of vision (**X1**), orienting movements such as movement of the head will facilitate vision. This would be followed by the suppression of bodily movement to reduce sensitivity to sound and startle, and to increase visual acuity (denoted by the arrow going from **O, D** to **U2, U3**, **U4** and **V2**). In summary, a visual orienting reflex to a “flash” would involve a reduction of the auditory orienting response to a “bang” and/or the motor orienting reflex following startle and vice versa. After a very short millisecond-level exposure, the defensive reflex (denoted by “D” in the box “**O, D”**) kicks in such as blinking of the eyes to protect against blinding light. Similar to the orienting reflex, the defensive reflex results in inverse responses in other sensory systems such as an increase in sensitivity to sound or a more intense motor response to startle as a function of the suppressed visual response to light (Sokolov 1963).

The orienting and defensive reflexes can be considered mediating variables in our pathway model in that they account for the relationship between the immediate effects of the flashbang (vision, hearing and startle) and the intensity of effects in other sensory systems (that is, the orienting and defensive reflex to “flash” influences hearing effects and motor effects). For the non-visually impaired population, vision is considered the dominant sense followed by hearing, touch, and smell/ taste (Spence 2009). The primacy of vision over the other senses appears to be well supported by our underlying biology. Humans, like other primates, display considerable visual specialization including high visual acuity, stereoscopic vision, trichromacy, and large visual cortices (Barton 2006). Some estimates suggest that up to 50% of the cortex may be involved in visual function (Palmer 1999). Experimental studies also support the dominance of sight over auditory perception and the speed of sensory responses to visual stimuli is quicker than to stimuli of other modalities (e.g., Colavita 1974; Spence 2009). Therefore, we can conclude that the orienting reflex to the “flash” would likely suppress the hearing effects of the “bang” and motor effects of startle more frequently than the other way around; likewise, the defensive reflex to the “flash” might make the individual more vulnerable to sound and startle.

B. Affective Shift

Affective shift, in our pathway model, refers to a change in the emotional state of the observer as a function of exposure to the flashbang. A substantial body of research has shown that the startle effect, in particular, is potentiated by situations that involve the processing of aversive information. Specifically, the magnitude of the eyeblink reflex (elicited by a “bang”) increases when an individual concurrently experiences a negative emotion. The “aversive stimulus → negative affect (fear) → startle” relationship has been termed “fear potentiated startle” and has been consistently demonstrated in experiments with animal subjects (Brown, Kalish, and Farber 1951). The converse of fear potentiated startle is “joy attenuated startle” and refers to the diluting effect of pleasant stimuli (and resulting positive affect) on the magnitude of the startle effect.

In parallel with the startle effect (denoted by **V1** in Figure 3) that comprises motor reflexes (**V2**) such as fast contractions of skeletal and facial muscles and closing of the eyes, the presentation of a “bang” leads to tinnitus (**U4** in Figure 2) and the associated blast overpressure leads to a spike in reported stress levels (**T5** in Figure 1–Figure 5) and the acceleration of heart rate (**T6** in Figure 1). In laboratory settings, the stimuli that are associated with this combination of reflexes are aversive and have been suggested to induce a state of fear or anxiety (**A** in Figure 1–Figure 5). The field of affective neuroscience has found that negative emotions are adaptive in that they lead to narrowing of attention to tasks that are very specific to removing or reducing the impact of the emotion-inducing-stimulus (Levenson 1994). For example, fear promotes the desire to flee and anger promotes the desire to fight (Rachman 1990). This increase in focus on the removal of the specific threat causes attention to be drawn away from other pre-planned activities. In our pathway model, we propose that the state of negative affect leads to one psychophysiological outcome—distraction (**Y1** in Figure 1–Figure 5). A sudden surge in negative affect serves as a powerful source of distraction from pre-planned actions (such as intent to shoot a target); this state of distraction, in turn, will exert a significant weakening influence on performance outcomes such as target detection (**Z1**), tracking accuracy (**Z2**) and targeting speed (**Z3**) illustrated in Figure 1–Figure 5. This shift in affect in the direction of negative emotions can be considered a moderator in this path diagram because it is a third variable that influences the relationship between the primary effects of the flashbang and their performance outcomes by triggering an intermediate unpleasant state of distraction.

8. Combined Effects and Conclusions

Having considered five separate human effects of flashbangs in the previous chapters, we need to understand their combined effects on human performance. **Figure 7** represents the integrated path diagram that combines the effects presented earlier in Figure 1–Figure 6, as well as illustrates the relationships between the variables presented in earlier sections. The asterisks in **Figure 7** represent inverse or negative relationships between variables. The absence of asterisks indicates positive relationships.

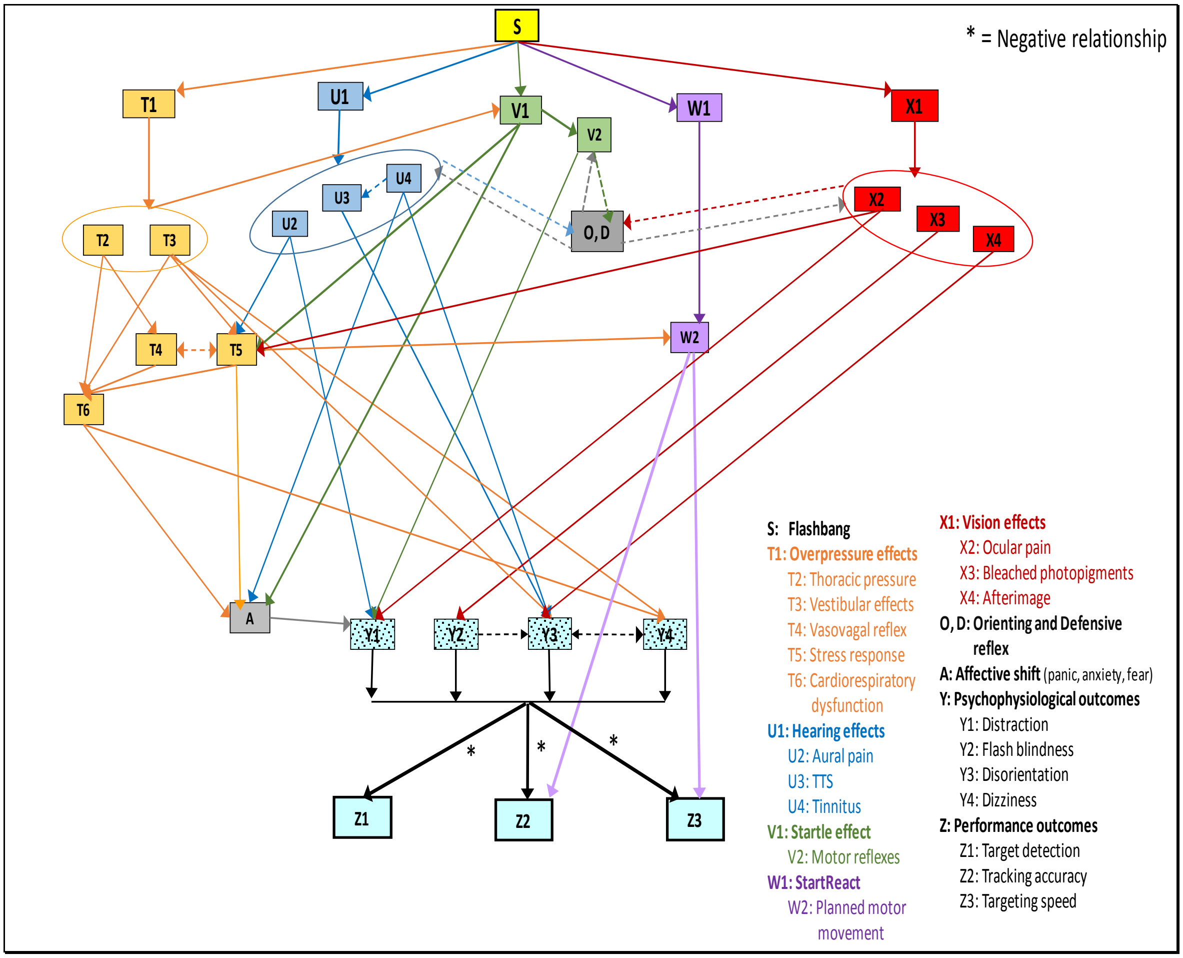


Figure 7. Path Diagram Representing Integrated Effects of Overpressure, Startle, StartReact, and Disrupted Hearing and Vision on Performance Outcomes

A prime example of integrated effects is presented at the center of **Figure 7** the startle reflex (**V1**). The startle reflex can be elicited through auditory, visual, or tactile stimuli, or a combination thereof. The reflex has a fixed and short latency (time delay between a stimulation and a response), which always begins within 0.1 seconds of a stimulus being perceived, usually sound (Rivera et al. 2014). In **Figure 7**, concurrent light and associated vision effects (**X1**) tend to enhance the experienced loudness of sounds (Odgaard et al. 2004); observers tend to judge a noise as louder when it is accompanied by a flash of light, even when sounds do not exceed 50dB. In terms of duration, the startle reflex lasts less than 1 second for a mild stimulus and in the range of 1 second to 1.5 seconds for a high-intensity stimulus. The startle reflex triggers increases in stress levels (**T5**) and leads to multifold effects in situations where stress is also impacted by vestibular shifts resulting from blast overpressure, aural pain resulting from the "bang" component of flashbangs and ocular pain resulting from the "flash" component of flashbangs. The stress response (**T5**) is a particularly important component of the path diagram in **Figure 7** because all components of the flashbang (sound, light and pressure) impact the stress response which is characterized by a quickening of heart rate, rapid breathing, muscle tension and sweating. Stress leads to a negative shift in affect (**A**), which serves as a moderator in the relationship between immediate and final performance effects of flashbangs. As can be seen in **Figure 7**, stress responses (**T5**) also impact planned motor movements (**W5**). StartReact (**W1**) is the only immediate response to flashbangs that lead to performance improvements by enhancing planned motor movements; in this situation, the stress response has a positive relationship with the outcome by enhancing the efficacy of motor movements leading to improved tracking (**Z2**) and targeting speed (**Z3**).

As indicated by "**O, D**" in **Figure 7**, the experience of a flashbang (pressure, sound and light) is followed by an initial orienting reflex ("**O"** in **O, D**) such as movement of the head to facilitate vision (in response to the flash). In parallel, this is accompanied by the suppression of bodily movement to reduce susceptibility of other senses to the flashbang. For example, an immediate visual reaction to a "flash" would involve an almost reflexive reduction of the auditory response to a "bang" in order to help the individual to "see" more clearly. A few milliseconds after the orienting reflex, a defensive reflex ("**D**" in O, D) follows that serves to protect or defend against the negative effects of the stimulus. In this case, a flash would lead to a defensive reflex such as blinking of the eyes. Contrary to the orienting reflex, the defensive reflex is accompanied by an increase in sensitivity of other sensory systems; that is, defensive blinking of the eyes is accompanied by an increase in sensitivity to sound. The orienting-defensive reflex can be thought of as a reciprocal relationship where orientation toward the "flash" leads to a suppression of response to the "bang" and vice versa.

In **Figure 7** "**O, D**" is a critical mediating variable because the potential of one flashbang effect (e.g., the vision effect) to suppress other effects (such as the hearing and startle effects) has implications for enhancing the effectiveness of one feature of the flashbang (such as "flash") over other features (such as the "bang"). Although we cannot draw definitive conclusions about relative effectiveness of each flashbang component (flash vs. bang, for instance) from the path diagrams alone, we can arrive at some conclusions based on the research that was used to derive the path diagrams. First, our research on hearing effects revealed that the effective sound level required for a single impulse noise to startle/disorient differs very little from that which is considered to be harmful to hearing. In comparison, research on vision effects suggests that the flash intensity required to produce a similar effect is more than an order of magnitude lower than the level causing vision damage, providing a workable safety margin in military and non-military applications. Second, the “flash” component of a flashbang might have stronger immediate effects than the “bang” component due to the visual system’s ability to dominate other senses; likewise, the defensive reflex to the “flash” might make the other senses more vulnerable. The strong vision effects relative to other senses suggests that the “flash” component may exert stronger immediate effects on human performance than the “bang” component.

9. Summary and Recommendations

Flashbang grenades are used to trigger behavioral changes in humans while minimizing the risk of significant injury. We examined the interaction of physiological and psychological responses to flashbang grenades to understand the processes driving measurable performance outcomes after exposure to a flashbang. Specifically, we used path analysis to identify what happens physiologically and psychologically between the deployment of a flashbang grenade and subsequent behavior change in the individual being subjected to the flashbang. Particular emphasis was placed on identifying relationships between immediate physiological effects such as eyeblink, intermediate psychophysiological effects such as distraction, and final measurable performance outcomes such as target detection, tracking accuracy, and targeting speed. Five effects were identified as the starting point of the analyses—overpressure effects, hearing effects, startle effect, StartReact (a cuing response that enhances a previously planned motor action), and vision effects. For each immediate effect, we traced a path between the first physiological reaction and intermediate psychophysiological states such as distraction, disorientation, and dizziness. The path(s) connecting intermediate and final outcomes were then identified.

A major finding of our analyses is that negative shifts in affect/emotion play a critical role in moderating the relationship between the immediate effects of flashbangs and final performance outcomes by narrowing attentional focus and distracting attention away from planned goals. Second, for the non-visually-impaired population, the visual system dominates other systems such as hearing and touch by suppressing or enhancing the sensitivity of other systems and weakening or strengthening other responses such as startle. Strong vision effects suggest that the “flash” may have the potential to lead to more immediate impact than the “bang” when the subject is visually oriented toward the flashbang. This requires further evaluation.

There are some issues to consider when measuring these variables in experimental settings. Proximity of the flashbang detonation to the subject and the topography/structure of the environment will influence the path model significantly. The variability in distance can be measured in training environments; however, the subjective nature of human response in terms of experienced pain, planned movements and performance outcomes can vary greatly. In addition to the five immediate flashbang effects considered in this report, one more variable to consider might be burn impact from the flashbang device. Physical impact of this nature may be rare in present day flashbangs; however, close proximity of the individual to detonation has been shown to have secondary and tertiary blast effects

(Angwin and Nehring 2015), which will have to be considered in an experimental setting. Although the path models presented in this report may not capture every interaction that might potentially occur as a function of flashbang exposure, they represent a comprehensive analysis of the variables that can be effectively measured in an experimental setting and the factors influencing those variables. We recommend that future efforts at improving the effectiveness of flashbang devices be focused on experimentally testing the variables and interactions identified by the path analyses in this report. Specifically, experimental paradigms must first establish the individual performance effects of flashbang components such as flash effects and bang effects. Once these effects have been established, they can be integrated into a comprehensive model that captures the interactions presented in the path diagrams in this report.

References

Angwin, J., and A. Nehring, A. 2015. “Hotter than Lava.” *ProPublica*: https://www.propublica.org/article/flashbangs.

Baron, R. M., and D. A. Kenny 1986. “The Moderator-Mediator Variable Distinction in Social Psychological Research: Conceptual, Strategic, and Statistical Considerations.” *Journal of Personality and Social Psychology* 51:1173–82.

Barton, R. A. 2006. “Olfactory Evolution and Behavioral Ecology in Primates.” *American Journal of Primatology* 68:545–58.

Bisdorff, A. R., A. M. Bronstein, and M. A. Gresty. 1994. “Responses in Neck and Facial Muscles to Sudden Free Fall and a Startling Auditory Stimulus.” *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section* 93 (6): 409–16.

Blumenthal, T. D., and W. Keith Berg. 1986. “Stimulus Rise Time, Intensity, and Bandwidth Effects on Acoustic Startle Amplitude and Probability.” *Psychophysiology* 23 (6): 635–41.

Blumenthal, T. D., B. N. Cuthbert, D. L. Filion, S. Hackley, O. V. Lipp, and A. Van Boxtel. 2005. “Committee Report: Guidelines for Human Startle Eyeblink Electromyographic Studies.” *Psychophysiology* 42 (1): 1–15.

Brown, J. S., H. I. Kalish, and I. E. Farber. 1951. “Conditioned Fear as Revealed by Magnitude of Startle Response to an Auditory Stimulus.” *Journal of Experimental Psychology* 41:317–28.

Carpenter-Thompson, J. R., S. Schmidt, E. McAuley, and F. T. Husain. 2015. “Increased Frontal Response May Underlie Decreased Tinnitus Severity.” *PLOS One* 10 (12): e0144419. https://doi.org/10.1371/journal.pone.0144419.

Casali, J. G., and G. S. Robinson. 1999. “Noise in Industry: Auditory Effects, Measurement, Regulations, and Management.” In *The Occupational Ergonomics Handbook*, 1st ed., edited by W. Karwowski and W. S. Marras, 1661–92. Boca Raton, FL: CRC Press.

Cernak, I., and L. J. Noble-Haeusslein. 2010. “Traumatic Brain Injury: An Overview of Pathobiology with Emphasis on Military Populations.” *Journal of Cerebral Blood Flow & Metabolism* 30 (2): 255–66.

Chan, M., and A. Singhal, A. 2015. “Emotion Matters: Implications for Distracted Driving.” *Safety Science* 72:302–9.

Chua, F. B., A. Daftari, T. L. Alvarez, R. DeMarco, M. T. Bergen, K. D. Beck, and R. J. Servatius. 2003. “Effect of Light Flashes on Saccadic Oculomotor Control.” In *Proceedings of 2003 IEEE 29th Annual Northeast Bioengineering Conference*, edited by Stanley Reisman, Richard Foulds, and Bruno Mantilla, 45–46. Piscataway, NJ: IEEE.

Chua, F. B., A. P. Daftari, T. L. Alvarez, R. M. DeMarco, M. T. Bergen, K. D. Beck, and R. J. Servatius. 2004. “Effects of a Single Green Flash Versus a White Flash of Light on Saccadic Oculomotor Metrics.” In *Proceedings of 2004 IEEE 30th Annual Northeast Bioengineering Conference,* edited by Steven Schreiner, July L. Cezeaux, and Diane M. Muratore, 9–10. Piscataway, NJ: IEEE.

Colavita, F. B. 1974. “Human Sensory Dominance.” *Perception & Psychophysics* 16:409–12.

DePalma, R. G., D. G. Burris, H. R. Champion, and M. J. Hodgson. 2005. “Blast Injuries.” *New England Journal of Medicine* 352 (13): 1335–42.

Garde, M. M., and A. Cowey. 2000. “‘Deaf Hearing’: Unacknowledged Detection of Auditory Stimuli in a Patient with Cerebral Deafness.” *Cortex* 36:71–80.

Gokin, A. P., and M. V. Karpukhina. 1985. “Reticular Structures of the Cat Brain Participating in Startle Reflexes in Response to Somatic Stimuli of Different Modalities.” *Neurophysiology* 17 (3): 380–90.

Graham, F. K. 1978. “Distinguishing among Orienting, Defense, and Startle Reflexes.” In (Eds.), *The Orienting Reflex in Humans*, edited by H. D. Kimmel, E. H. Van Olst, and J. F. Orlebeke, 137–67. New York, NY: Lawrence Erlbaum Associates, Inc.

Hackley, S. A., and F. Valle-Inclan. 1998. “Automatic Alerting Does Not Speed Late motoric Processes in a Reaction-Time Task.” *Nature* 391 (6669): 786.

Howarth, P. A., G. Heron, D. S. Greenhouse, L. L. Bailey, and S. M. Berman. 1993. “Discomfort from Glare: The Role of Pupillary Hippus.” *International Journal of Lighting Research and Technology* 25 (1): 37–42.

Hupé, J. M., C. Lamirel, and J. Lorenceau. 2009. “Pupil Dynamics during Bistable Motion Perception.” *Journal of Vision* 9 (7): 10.

Jepma, M., E. J. Wagenmakers, G. P. Band, and S. Nieuwenhuis. 2009. “The Effects of Accessory Stimuli on Information Processing: Evidence from Electrophysiology and a Diffusion Model Analysis.” *Journal of Cognitive Neuroscience* 21 (5): 847–64.

Krahenbuhl, G. S. 1975. “Adrenaline, Arousal and Sport.” *The Journal of Sports Medicine* 3 (3): 117–21.

Krohn, P. L., D. Whitteridge, and S. Zuckerman. 1942. “Physiological Effects of Blast.” *The Lancet* 239 (6183): 252–59.

Levenson, R.W. 1994. “Human Emotions: A Functional Review.” In *The Nature of Emotion: Fundamental Questions*, edited by P. Ekman and R. Davidson, 123–26. New York: Oxford University Press.

Licklider, J. C. R., and G. A. Miller. 1951. In *Handbook of Experimental Psychology,* edited by S.S. Stevens, 1063–64. John Wiley Sons Inc. New York.

Linton, S. J., and W. S. Shaw. 2011. “Impact of Psychological Factors in the Experience of Pain.” *Physical Therapy* 91 (5): 700–711.

Loeb, M. 1986. *Noise and Human Efficiency*. John Wiley & Sons.

MacKinnon, C. D., D. Bissig, J. Chiusano, E. Miller, L. Rudnick, C. Jager, and M. W. Rogers. 2007. “Preparation of Anticipatory Postural Adjustments Prior to Stepping.” *Journal of Neurophysiology* 97 (6): 4368–79.

McManis, M. H., M. M. Bradley, W. K. Berg, B. N. Cuthbert, and P. J. Lang. 2001. “Emotional Reactions in Children: Verbal, Physiological, and Behavioral Responses to Affective Pictures.” *Psychophysiology* 38 (2): 222–31.

Nieuwenhuijzen, P. H. J. A., A. M. Schillings, G. P. Van Galen, and J. Duysens. 2000. “Modulation of the Startle Response during Human Gait.” *Journal of Neurophysiology* 84 (1): 65–74.

Odgaard, E. C., Y. Arieh, and L. E. Marks. 2004. “Brighter Noise: Sensory Enhancement of Perceived Loudness by Concurrent Visual Stimulation.” *Cognitive, Affective, & Behavioral Neuroscience* 4 (2): 127–32.

Queralt, A., V. Weerdesteyn, H. J. Duijnhoven, J. M. Castellote, J. Valls-Solé, and J. Duysens. 2008. “The Effects of an Auditory Startle on Obstacle Avoidance during Walking.” *The Journal of Physiology* 586 (18): 4453–63.

Palmer, S. E. 1999. *Vision Science: Photons to Phenomenology*. Cambridge, MA: Bradford Books.

Rachman, S. J. 1990. *Fear and Courage.* 2nd ed. New York: W.H. Freeman.

Reynolds, J. Z. 2012. “Testing the ‘Interrupt Hypothesis’: Does Startle Disrupt Cognitive Processing?” PhD dissertation, Wake Forest University.

Rivera, J., A. B. Talone, C. T. Boesser, F. Jentsch, and M. Yeh. 2014. “Startle and Surprise on the Flight Deck: Similarities, Differences, and Prevalence.” In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 58, no. 1: 1047–51. Sage, CA; Los Angeles, CA: SAGE Publications.

Robertson, A. G. 2005. “The Medical Effects of Non-lethal Weapons–A Review.” *Australian Military Medicine* 14 (2): 66.

Schepens, B., and P. J. Delwaide. 1995. “Modifications of Audio-Spinal Facilitation during Gait in Normal Man.” *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control* 97 (6): 424–31.

Schmidt, R. T. 1999. “Reduce Risk of Inducing Spatial Disorientation Using Physiologically Compatible Ground Lighting.” *Aviation, Space, and Environmental Medicine* 70 (6): 598–603.

Sokolov, E. N. 1963. “Higher Nervous Functions: The Orienting Reflex.” *Annual Review of Physiology* 25 (1): 545–80.

Spence, C. 2009. “Explaining the Colavita Visual Dominance Effect.” *Progress in Brain Research* 176:245–58.

Stone, P. T. 2009. “A Model for the Explanation of Discomfort and Pain in the Eye Caused by Light.” *Lighting Research & Technology* 41 (2): 109–21.

Stringham, J. M., K. Fuld, and A. J. Wenzel. 2003. “Action Spectrum for Photophobia.” *JOSA A* 20 (10): 1852–58.

Szalma, J. L., and P. A. Hancock. 2011. “Noise Effects on Human Performance: A Meta-analytic Synthesis.” *Psychological Bulletin* 137 (4): 682.

Tikuisis, P., M. Ponikvar, A. A. Keefe, and S. M. Abel. 2009. “Target Detection, Identification, and Marksmanship during Battlefield Noise in a Synthetic Environment.” *Military Psychology* 21 (2): 186–99.

Valls-Solé, J., A. Solé, F. Valldeoriola, E. Munoz, L. E. Gonzalez, and E. S. Tolosa. 1995. “Reaction Time and Acoustic Startle in Normal Human Subjects.” *Neuroscience Letters* 195 (2): 97–100.

VanMeenen, K. M., K. R. Short, R. M. DeMarco, F. B. Chua, M. N. Janal, and R. J. Servatius. 2006. “Suppression: Sound and Light Interference with Targeting.” In *Proceedings of SPIE: Enabling Technologies and Design of Nonlethal Weapon* 6219:62190J.

Wang, L., P. Goldmann, and B. Tengroth. 1990. “Effect of Spectral Flash on Readaptation Time.” *Aviation, Space, and Environmental Medicine* 61 (2): 125–31.

Waters, C. E., R. G. Mistrick, and C. A. Bernecker. 1995. “Discomfort Glare from Sources of Non-uniform Luminance.” *Journal of the Illuminating Engineering Society* 24 (2): 73–85.

Wegner, M., J. M. Koedijker, and H. Budde. 2014. “The Effect of Acute Exercise and Psychosocial Stress on Fine Motor Skills and Testosterone Concentration in the Saliva of High School Students.” *PloS One* 9 (3): e92953.

Zucker, I. H. 1986. “Left Ventricular Receptors: Physiological Controllers or pathological Curiosities?” *Basic Research in Cardiology* 81:539–57.

Zuckerman, S. 1940. “Experimental Study of Blast Injuries to the Lungs.” *Lancet II* 236:219–24.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE November 2018	2. REPORT TYPE Final	3. DATES COVERED *(From–To)* JUL 2018 – NOV 2018

4. TITLE AND SUBTITLE

Path Analysis of Human Effects of Flashbang Grenades

5a. CONTRACT NUMBER
HQ0034-14-D-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Madhavan, Poornima
Dobbins, Christian

5d. PROJECT NUMBER
DU-2-4106

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, VA 22311-1882

8. PERFORMING ORGANIZATION REPORT NUMBER

IDA Document D-9270

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Joint Non-Lethal Weapons Directorate
3097 Range Road
Quantico, VA 22134-5100

10. SPONSOR/MONITOR’S ACRONYM(S)

JNLWD

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited (12 April 2019).

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report provides a detailed path analysis of human responses to flashbang grenades, their relationship with performance outcomes, and their implications for the design of human-subject experiments to quantify these effects. IDA used path analysis to identify what happens to the individual physiologically and psychologically after the deployment of a flashbang grenade. Five immediate effects were identified as the starting point of the analyses—overpressure effects, hearing effects, the startle effect, StartReact effects, and vision effects—each corresponding with unique physiological effects on the human body. For each immediate effect, we traced a path between the first physiological reaction and intermediate psychophysiological states such as distraction, disorientation, and dizziness. The path from intermediate psychophysiological effects and final performance outcomes was then identified. The report suggests that there are ways to enhance the human effectiveness of flashbang grenades without raising the risk of significant injury. IDA recommends that future efforts at improving the effectiveness of flashbang grenades be focused on experimentally testing the variables and interactions identified by the path analyses presented in this report.

15. SUBJECT TERMS

Blast Overpressure; flashbang grenades; hearing effects; human behavior; Non-Lethal Weapons; path analysis; psychology; startle effect; visual effects

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Dr. Shannon Foley
a. REPORT Uncl.	b. ABSTRACT Uncl.	c. THIS PAGE Uncl.	SAR	38	19b. TELEPHONE NUMBER *(include area code)* 703-432-0916