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ARTICLE TITLE: Distraction for the eye and ear

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THEORETICAL RESEARCH ARTICLE: **Distraction for the eye and ear**

Abstract

The ways that extraneous visual and auditory stimuli impair human performance are reviewed with aim of distinguishing those sensory, perceptual and cognitive effects relevant to the design of human-machine systems. Although commonly regarded as disruptive, distractions reflect the adaptability of the organism to changing circumstances. Depending on the context, our knowledge of the ways in which distraction works can be exploited in the form of alarms or other attention-getting devices, or resisted by changing the physical and psychological properties of the stimuli. The research described here draws from contemporary research on distraction.

The review underscores the vulnerability of performance even from stimuli of modest magnitude while acknowledging that distraction is a necessary consequence of our adaptive brain that leads to effects that are (and sometimes, but not always) beneficial to safety, efficiency and wellbeing. Low intensity distractors are particularly sensitive to the context in which they occur. The mechanisms outlined can be exploited either to grab attention (and even temporarily disable the individual, but more usefully to warn or redirect the individual) or to modify it in subtle ways across the gamut of human activity.

Key words: auditory distraction, visual distraction, cognitive distraction, human performance

Commentators on social habits are quick to condemn the contemporary fashion for information-rich watches, phones and other paraphernalia of a digital life-style, characterizing them as contributing to distraction and therefore a threat to the good of society and at the extreme an addiction, disease or again, a plague. Yet, distractibility is an essential core characteristic of an adaptive organism. Having the means to notice, register and respond to the unpredicted and un-planned-for provides an opportunity to adapt to chance means that distraction is essential

Distraction is a term that covers a wide range of meanings; this article covers the effect of external distracting events. We exclude from discussion distraction that arises from what we might describe as states of mind, that is, distraction of ideational origin, or mind-wandering. The focus here is on behavior in human-machine systems and the way that distraction can impair performance and wellbeing as a result of physical energy entering the senses. We examine the most dominant senses—hearing and vision.— thereby giving coverage to the most frequently encountered sources of distraction while at the same time noting similarities and differences in sensory and perceptual determinants of distraction across modality, which leads on naturally to ways in which distraction appears to be transcendent.

The breath of topics covered in the review is wide and various, combining a considerable body of research using simple tasks to focus on relevant psychological processes as well as findings from research that has sought to apply such findings to more complex settings (see Table 1). Factors that exacerbate distracting effects, as well as approaches to mitigating the various effects are also discussed.

We have restricted references to one or a few associated with substantive empirical contributions. We have used the ploy of citing the most recent relevant reference in each case in order to give the most contemporary pointer for the reader.

The eye

Given the visual system’s complexity and dominance it comes as no surprise that the issue of visual distraction has been addressed from the effects of basic physical properties of light. In addition, basic processes involved in utilizing visual information have also been isolated and analyzed, such as the ability: to identify simple ‘targets’ in an array of simple objects (e.g., detecting a green circle in a display containing various shapes of various colors. Types of distraction investigated in this research include those effects that impede the visual sense itself, for example, by causing temporary *flash blindness*; the effects of distractor stimuli that reduce the resolution with which target information may be perceived.

Intense light

Exposure to very strong light causes a profound loss of capacity to see—sometimes accompanied by distraction and disorientation— some of which is irreversible, though only reversible effects are considered here (e.g., McKinlay & Harlen, 1984). Short-term loss may be accompanied by distraction, disorientation and even incapacitation. The impact of an exposure depends not only on the energy contained in the light, but also on the exposed individual's activity, psychological state, adaptation level and the current visual task.

Flash blindness: Temporary visual impairment such as glare or flash blindness can seriously degrade the performance of tasks that require vision. Glare is defined as the momentary visual loss that occurs while the light source is on. Flash blindness is a temporary visual loss following a brief exposure to an abrupt increase in the brightness of all or part of the field of view (Randolph, Schmeisser, & Beatrice, 1985) that continues after the termination of the exposure. Temporary visual impairment can be localized (small part of the visual field) or global (entire visual field). During flash blindness virtually nothing is visible in the affected parts of the retina except the afterimages of the light (Randolph et al., 1985). Depending on the adaptation state of the eye and the exposure level, flash blindness may last up to several minutes.

Most people will have encountered glare (sometimes called *dazzle*) which takes the form of temporary inability to see details around a bright light (such as the headlights of an oncoming car) but this is not associated with biological damage and lasts only as long as the bright light is actually present. Temporary visual disability results from diffractions and scattering of light inside the eye due to the imperfect transparency of the optical media and to a lesser extent by diffuse light passing through the scleral wall or the iris (Commission International de l'Éclairage CIE, 2002). The scattered light overlays the retinal image, thus reducing visual contrast and impairing vision (a ‘veiling’ luminance) by reducing contrast.

The temporary loss of vision arising from a single flash results from the bleaching of retinal light-sensitive pigments. An afterimage, which moves with the eye, and which may persist for several seconds up to several minutes, is the result of a temporary scotoma (blind spot) that either partially or completely obscures vision.. Recovery depends on a range of factors including target contrast, brightness, color, size, observer age, and the overall adaptation state of the visual system (e.g., Wütrich, Schmid, Lüthy, & Weber , 1997). Complete dark adaptation of the visual system takes 20 to 30 minutes

(Davson, 1976) whereas the opposite (adaptation to bright light) is complete within two minutes (Megaw, 1992) all of which points to the fact that night-time ambient light levels will render flash blindness most disruptive.

Flicker: Lights that flicker in intensity in the range 2–25Hz are subjectively discomforting. The degree of discomfort depends on the modulation depth (maximum to minimum light level) and the intensity-time profile of the flicker (Bartley & Nelson, 1961): short flashes in which the duration of the on-cycle is less than 25% of the total on-off cycle (the so-called pulse-to-cycle ratio: Bartley & Nelson, 1961) are visually most discomforting. When retinal illuminance is fixed (i.e., the amount of light falling upon the eye) the discomfort increases with decreasing light source area (e.g.,Alferdinck, 1996).

Effects of luminance flicker (intensity modulation of bright lights) go beyond the purely visual, resulting at times in vertigo, disorientation, mild headaches and muscle spasm to convulsions or epileptic seizures (Harding & Jeavons, 1994).

Chromatic flicker (color changes of bright lights) can trigger sustained cortical excitation even in normal subjects, which is largest at a driving frequency of 10 Hz, and strongest for Red/Blue flicker, followed by Blue/Green and Red/Green (Watanabe, Imada, Niheui, & Shimojo., 2002). Red-blue flicker is most provocative below 30 Hz (e.g., Yamasaki, Goto,Kinukawa, & Tobimatsu 2008). As with brightness flicker, performance of mental tasks can be immune to flicker that is judged uncomfortable (Alferdinck et al., 2010).

Moderately intense visual stimuli

Here interest centers on the effect of the brief presentation of various shapes, objects or images of modest intensity while undertaking a visual task such as detecting or identifying visual objects or events.

Detecting changes in scenes: Change blindness. Flashing lights can capture attention, reduce the likelihood of a change being detected and impair the search for an object of interest. It is very difficult to spot changes occurring in a scene if the changes in luminance or motion that accompany them are obscured: *change blindness* (Simons & Rensink, 2005). For instance, two versions of the same image—a military transport plane—are shown in rapid succession with, critically, a blank grey slide in-between. In one of the images an under-wing jet engine (which appears towards the middle of the image) has been removed. On average, it takes a naive observer about 40s to notice the difference. This difficulty arises because the grey slide obscures the transients that identify differences between scenes. Without the blank slide the absence of the engine would be signified by marked localized luminance change in that portion of the image.

A whole-field flash would be expected to have a similar effect to the blank slide in a flicker task. Any changes that occurred during the flash would be obscured. The operator would need to search for changes, comparing what can be seen against what can be remembered. The difficulty of comparing the current scene to a memory of the scene is illustrated by viewers' unawareness of continuity errors in films, such as when changes of clothes by an actor that occurs before and after a cut, go unnoticed.

More localized flashes are also disruptive. Rather than insert a blank frame as in the just described flicker experiment, a "mud-splash" is added to the display (O'Regan, Rensink, & Clark, 1999). This reduces the ability to detect simultaneous changes elsewhere in the scene. The primary determinant of the effectiveness of light flashes on change blindness is the number of flashes that occur (see Gusev, Mikhaylovab, & Utochkinc, 2014). Localized flashes may also capture attention and relocate the more sensitive part of the eye, the fovea, in their direction. In addition, localized flashes can disrupt temporal order judgments (Cass & Van der Burg, 2014).

Change blindness seems to be a phenomenon that transcends sensory modality. It has been demonstrated to occur in hearing (e.g. Dalton & Fraenkel, 2012) and tactile perception (e.g. Gallace, Tan, & Spence, 2006). Furthermore, there is evidence of cross-modal effects in detection of change. At high visual workload, ability to detect tactile events (tap on the palm) is diminished, a result which is in line with visual load reducing sensitivity to unexpected (Macdonald & Lavie, 2011) and expected auditory events (Murphy & Dalton, 2016; Raveh & Lavie, 2015). Therefore, visual flashes reduce sensitivity to change in non-visual modalities and bangs reduce sensitivity to change in non-auditory modalities.

A localized flash involuntarily captures attention that results in increased reaction times to the target information. The critical features of capture are the change in luminance (Enns, Austen, Di Lollo, Rauschenberger, & Yantis, 2001) and the appearance of a new object (Jonides & Yantis, 1988). A localized flash has both of these features: the luminance changes markedly and the onset of the light creates a new “object” (a disk of light). Although a flash can capture attention, the observer can very quickly switch attention elsewhere. A sequence of flashes, especially if they were in different locations, is likely to be more disruptive.

Object attentional capture. Object movement can capture attention. Lateral translation (i.e., steadily moving across), lateral jitter (rapid movement back and forth) and looming (object getting larger) have all been shown to capture attention (Franconeri & Simons, 2003).

Usually, in naturalistic settings the observer is not stationary so that motion results across the retinal image. However, the brain is able to filter out retinal motion that results from self-movement (‘flow-parsing’)so that visual search proceeds as normal (Rushton, Bradshaw, & Warren, 2007). Furthermore, attentional capture seems to be unaffected by observer movement, suggesting that the same type of distracting effects will occur whether the operator is stationary or moving.

If an array of static objects rapidly changes in contrast (moving between black, grey and white) a global flicker is perceived which will help to detect the change. However, if the array of objects is rotated or moved the perceived flicker is abolished or reduced, which makes detecting the change harder, known as motion silencing (Suchow & Alvarez, 2011).

A related effect is found when an array of points is moved over a set of objects, the objects may seem to disappear, known as motion-induced blindness (e.g.,Bonneh, Cooperman, & Sagi, 2001). It lasts longer than the motion silencing effect and it relies on maintaining fixation. A ‘discoball’ type pattern superimposed on a scene might consequently be expected to impair detection of change (motion silencing), and ultimately even impair perception of the presence of objects (motion induced blindness).

Whole-field and localized flashes, whether moving or stationary would be expected to mask important changes. The disruption associated with localized flashes is likely to be due to two mechanisms, namely low-level masking and attentional capture. The impact of the two mechanisms is likely to be dependent on the spatial distribution of the flashes (see Bonneh, et al., 2001).

Identifying Targets. When Identifying targets in visual displays*,* two types of effect can be distinguished depending on whether the distracters are near the targets (crowding) or more widely distributed (visual search). In the first case, distracters impair the visual identification of targets while in the second case they interfere with the deployment of visual attention. Research on crowding mostly involves identifying shapes when surrounded by other shapes and is therefore quite distinct in type from flash-induced blindness. Crowding and attentional capture probably both contribute to the distracting effect of flashes when these occur close to the target.

The presence of nearby elements in the visual field severely disrupts target perception. Objects th

at can be easily identified in isolation seem jumbled and indistinct in clutter. Crowding does not affect target *detection* (i.e., noticing that a target is present): it only impairs *identification* (i.e., knowing what that target is). It is generally assumed that crowding results from either *pooling* (observers simply cannot distinguish individual item features because these are already combined across stimuli at an early stage in the visual processing chain), *substitution* (observers can access individual item features but confuse or swap their position within the scene; see e.g., Ester, Zibler, & Serences, 2015), or the *poor resolution of spatial attention (*observers are not able to resolve features that are too close together in space*;* Intriligator & Cavanagh, 2001*)*.

Visual search typically requires observers to search repeatedly for a target (defined by color or shape) among distractor items (Wolfe, Oliva, Horowitz, Butcher, & Bompass, 2002).

Fore-knowledge about the non-targets increases the efficiency of search. Reliable effects of flashes have been found on the preview effect (Watson & Humphreys, 1997) in visual search. This preview benefit is abolished when dynamic visual noise (visual ‘static’) occurs after the preview stage, suggesting that global changes such as from a flashing flood light, might abolish preview benefits and hence slow visual search (see

Osugi & Murakami, 2015).

Global changes in luminance are likely to impair the tracking of four or five simultaneously moving objects (Pylyshyn & Storm, 1988). This is predicted because multiple object tracking relies on motion processing mechanisms (Clair, Huff, & Seiffert, 2010), and global changes in luminance would inhibit such mechanisms.

Effects of and on cognition. More generally, task-irrelevant visual distractors, be they flashes or objects, will interfere with cognitive processing of task-relevant information. Visual distracters add cognitive load (Kristjánsson, Heimisson, Róbertsson, & Whitney, 2017), which will impact on learning and working-memory, reduce the available capacity to devote to the task-relevant information (e.g., Miendlarzewska, Van Elswijk, Cannistraci, & van Ee, 2013). When distractors are natural images rather than flashes, the valence of distracters (negative *vs.* positive or neutral emotions conveyed by words or facial expression or threatening images) change performance (e.g., D'andrea-Penna, Frank, Heatherton, & Tse, 2017). Negative or unpleasant images decrease task performance, while positive images can sometimes improve performance, although the pattern is sometimes reversed when the task is to identify negatively-valenced targets (Jackson et al., 2012).

Exploration of the visual world involves frequent jumps of the eye (on average three times per second in natural viewing conditions), known as saccades, alternating with brief periods of fixation. Saccades are delayed when irrelevant stimuli appear in the visual field, so called *saccadic inhibition* (Bompas & Sumner, 2011, 2015). The eyes are diverted towards the distracters, away from target information. Typically, lights briefly flashed during an eye movement affect the latency, velocity, trajectory and extent of both regular saccades and fixational eye-movement (e.g., Buonocore, McIntosh, &

Melcher, 2015). Similar effects are observed in visually-controlled grasping movements and to a lesser extent in pointing (Colman, Remington & Kritikos, 2017), as well as fast action selection involving button presses. Maintaining good performance despite the presence of distractors involves some extra top-down signal to suppress this task-irrelevant information and make sure the eyes/hands/fingers are directed to the target.

Presence of a threat brings on a plethora of changes: to the startle response (Brown, Kalish, & Farber, 1951), to low-level visual processing (e.g. enhancement of sensory sensitivity; Shackman, Maxwell, McMenamin, Greischar, & Davidson, 2011), to patterns of eye movements (saccades towards the threat source are increased; e.g, Nissens, Failing, & Theeuwes, 2017) and changes in attentional focus (Schmidt et al., 2015) that can persist after the threat stimulus has been removed (Preciado et al., 2017). Under threat, observers are more likely to interpret an ambiguous situation negatively than when not under threat (Neta, Cantelon, Haga, Mahoney, Taylor, & Davis, 2017). Threat of an electric shock was associated with an increased tendency to interpret an ambiguous facial expression as indicating a negative emotion (e.g., anger). Therefore, task-irrelevant visual distractors may have a negative impact on performance, even if the flashes themselves are not particularly unpleasant or disruptive, but are associated with the chance of unpleasant experiences to follow.

The impact of threat has also been reported to be greatest in conditions in which the outcome is not entirely predictable. Anxiety and startle response tend to be higher when a shock may occur than when it will occur (Grillon, Baas, Cornwell, & Johnson, 2006). The impact of threat can be reduced when the observer anticipates a reward for overcoming the threat, so monetary rewards abolish the impact of threat-related stimuli (Sussman, Szekely, Hajcak, & Mohanty, 2016). Whether the rewards need to come from an external source or whether an internal sense of accomplishment or preservation of well-being would be sufficient has not been addressed.

Changes in background texture. Few studies have investigated the effect of irrelevant visual stimuli on higher-level cognitive processes. One line of evidence that is now receiving a resurgence of interest suggests that even quite modest changes in the visual texture of the scene—without any sort of accompanying threat or startle—have effects on a range of memory tasks (see Chubala, Surprenant, Neath & Quinlan, 2018, for an overview). By way of distraction each pixel on a display screen is randomly set either to black or white and every second a small random number of them changes state, a manipulation known as dynamic visual noise (see Quinn & McConnell, 1996) while a short-term memory task is undertaken auditorily. Although task and distractor are in different modalities, mere exposure to the dynamic visual noise produces a reduction in memory, suggesting that some automatic processing of the visual display occurs, and that the result enters the cognitive system and proves disruptive. However, the results seem to vary across task type and task stage.

Not all memory tasks are equally susceptible to dynamic visual noise. An early study (Quinn and McConnell, 1996) found that dynamic visual noise produced no effect on rote memory, only when the words involved a visual imaging strategy for their retrieval. This result has been replicated a number of times (e.g., Andrade, Kemps, Werniers, May & Szmalec, 2002; Chubala, et al., 2018; McConnell & Quinn, 2000; Quinn & McConnell, 1999). An analogous finding is that paired associate memory was vulnerable to dynamic visual noise, but serial recall was not (Ueno & Saito, 2013). By contrast if irrelevant speech is presented while a visual memory task is undertaken the effects are strongest for serial recall, generally speaking serial processing tends to be most sensitive, with tasks that do not involve serial order showing markedly less sensitivity (e.g., Beaman & Jones, 1997; Macken & Jones, 2003; see also below).

Similarly, not all stages of a memory tasks seem equally susceptible to disruption. Dynamic visual noise presented during an interval over which the verbal stimuli were retained does not produce disruption, but there is an effect at presentation and recall (Andrade et al., 2002; Avons & Sestieri, 2005; Quinn & McConnell, 2006). Others found effects of dynamic visual noise during backward serial recall but not forward (St Clair-Thompson & Allen, 2013, Experiment 3). By contrast, irrelevant speech produces effects broadly similar in presentation, retention and recall stages of the task (Miles, Jones & Madden, 1991; Norris, Baddeley & Page, 2004). Dynamic visual noise eliminates the standard benefit of concrete over abstract words (but only in delayed free recall and delayed recognition tasks, Parker and Dagnall, 2009; see also Chubala, et al., 2018). More frequent changes in dynamic visual noise produce greater disruption (see Dean, Dewhurst, & Whittaker, 2005; McConnell & Quinn, 2000; Quinn & McConnell, 1999) and the more changes to the speech, also the greater the disruption (see for example, Beaman & Jones, 1997 and below). Clearly, the effect is a complex one, but interesting also given the ubiquity of potential sources of distraction.

The majority of the research summarized so far is based on simple laboratory tasks involving minimal displays that have little resemblance to real world situations. An open question is the degree to which such studies can be extrapolated to more ‘real world’ applications.

Simulations of real-world settings*:* Detection of roadway changes—such as brake lights from other cars—is impaired following a camera flash recording drivers going through red lights in a way consistent with laboratory effects: at short flash-brake-light intervals detection was faster when the camera flash was on the same side of the road as the braking car (a ‘cueing’ effect), at longer asynchronies the detection was slower, suggesting attention was drawn to the task-irrelevant flash and had to be redirected to the target brake light information (Sall, Wright, & Boot, 2014).

Laser dazzling disrupts car maneuvering performance in twilight and darkness but not in daylight (Steinvall et al., 2013). At night-time ‘jamming’ of human vision can be achieved with dazzle (i.e. glare) or flash blindness well within the safety margins of eye damage. During day-time the intensity of the disrupting light source has to compete with the ambient (sun) light, resulting in effective glare or dazzle intensity levels exceeding eye-safe threshold levels. Light flashes disturb targeting, and more so for shots at more distant (smaller) targets (see e.g., Alferdinck et al., 2010). Typically, these effects are pronounced in civilians, but have little effect on shooting performance of soldiers (see, Griffioen-Young, 1999).

In contrast to tasks involving searching for target information in a visual scene, driving and tracking performance appear relatively insensitive to luminance or chrominance (color) flicker (Alferdinck, et al. 2010). Therefore, one way to protect against change blindness induced by flashes is to ensure that any important changes (such as a visual warning signal on a display console) are indicated not by a single change from one state to another, but rather by a repeating change.

Distraction for the eye: Routes to Mitigation

It may be useful to summarize some of the key factors that modulate visual distraction all the while remembering that their action depends on the context in which they appear. It should be remembered too that although we have cast it as mitigation here, there may be settings in which distraction is desirable or necessary, in which case our narrative can be inverted. In terms of mitigation, some of the factors that need to be taken into consideration are as follows:

The strength and location of the distracting source needs to be considered. In emergency and non-routine settings these may not be at the discretion of the user or system designer. Any medium that reduces the distractor visual strength by reducing the contrast compared to background (typically bright lights against a dark background) is the easiest solution (Bompas & Sumner, 2011). Of course, wearing lenses that are not adaptive will mean that for the most part vision will be impaired in-between flashes.

Any measure that can reduce the proximity of the distractor and the target will reduce distraction (typically, spot lights aimed toward the object of attention are most powerful: Verbruggen, Stevens, & Chambers, 2014), but absolute location is also important (lower visual field distractors produce stronger interference, bilateral distracters are also harder to ignore because it prevents tuning one’s attention to one hemifield only: Kaft, et al., 2007).

With light of lower intensity the overlap in visual features (color, shape, etc.) between distractors and targets becomes important (it is easier to find orange targets among blue distractors than among distractors that are red and yellow: D’ Zmura, 1991). This is an important design consideration when trying to reduce distraction. As stimuli become more complex, such as when distractors are objects, the semantics of distracters modulate the distraction (for instance, faces automatically draw attention: Wilkinson, & Light, 2011) that also has implications of the findings on the variability of distracters (diverse distractors are harder to ignore, while repetition in time or space reduces their impact: e.g., Cohen Kadosh, Gevers, & Notebaert, 2011). With several of these qualifications in mind the general rule is that as the number of distractors increases, so does the likelihood of distraction (although the effect is not straightforward, when distracters are all the same, low and high numbers are easier to ignore: Rangelov, Müller, & Zehetleitner, 2013). Of course, it is important to remember that some task contexts are dynamic, that is populated by a changing cast of symbols and visual forms. So, targets' variability, predictability and number become important considerations in such settings. It is harder to search for something that can take multiple forms (e.g., Rangelov, et al., 2013), or has too many concurrent targets (which increases cognitive load, Kristjansson, et al., 2013). Repeated or expected targets are less prone to interference (Marini, van den Berg, & Woldorff, 2015). It follows that expectation of a distractor's visual feature content or predictability (expectation regarding the target's visual features and time of occurrence) can help differentiate it from irrelevant distractors (Couperus & Mangun, 2010).

Concurrent workload seems to be an important factor: Visual tasks with a high cognitive component are correspondingly sensitive to the cognitive context in which they are undertaken, so that high cognitive-control load (multi-tasking, time pressure, threat) increases distractor interference (Lavie, 2005).

Really quite minor physical global changes to the background seem to impair complex task performance even when the task itself is not visual (see Chubala, et al., 2018) and while this research is in its infancy it may prove to be an important and ubiquitous phenomenon.

To summarize, the effects of visual distraction on performance are often largely automatic, but knowledge of the properties of targets and/or distractors (visual features, spatial location, probability of occurrence, etc.) on the part of the system designer can be used to guide the deployment of attention and action and help mitigate the interference from distractors. Hence, everything that helps differentiate relevant (target) from irrelevant information (distractors), making it possible to selectively facilitate the former and inhibit the later, will reduce the interference from distracters (see e.g., Guerreiro, Eck, Moerel, Evers, & Van Gerven, 2015; for brain mechanisms).

The Ear

The human hearing system has been described as the ‘sentinel of the senses’ because it possesses a unique combination of qualities that make it an exquisite warning system.: unlike vision it is omnidirectional, capable of registering information during the hours of sleep and darkness, and—if sufficiently loud—the source can be both very remote and obscured and still act as a basis of action. In other ways too audition is distinct from vision. Unlike most visual events, auditory events are evanescent, in that they are fleeting. This may in part account for the fact that auditory perceptual processing is exquisitely sensitive to transient events like the breaking of twigs underfoot that might herald less-than-benign events. For our remote ancestors, whether in woodland or the savannah, the capacity to both detect and locate predator or prey will have contributed significantly to survival and in turn to the growing capacity of the brain to detect distracting events. Increasingly sophisticated hearing mechanisms were at the core of the dynamic interaction of change to upright posture, the increasing complexity of vocal tract, the evolution of language and the benefits of social enterprise among others, that gave *Homo* its evolutionary edge (see Beaman, 2010, for a discussion).

We adopt the same progression we used for the eye, that is by discussing high intensity sound before going on to discuss sounds of moderate and low intensity.

High Intensity Sound

As a general rule sounds above about 80dB (about the sound of busy city traffic) are taken here to be ones of high intensity, even though at the lower end of this range the sound does not necessarily lead to discomfort for the listener. Nonetheless, there are a number of distracting effects that are only observed for sounds that reach or exceed this level of intensity, while many other effects are observable at much lower intensities. The *startle* response is the most widely researched and understood effect of a burst of high intensity sound on human performance. Other effects of high intensity sound include temporary changes in hearing sensitivity, as well as possible effects on other physiological systems (though in this latter case research is sparse because of the harm that could befall human volunteers). First, we turn to startle.

Startle: A whole-body reaction.

In principle, any sudden, intense stimulus may elicit a startle response—acoustic, visual, vestibular, tactile or electrical—but auditory startle is by far the most frequently studied. Physical determinants of startle include intensity, duration and frequency. To elicit a startle response the sound must be 85dB or greater, the magnitude of the response tending to increase with increasing intensity. Sounds of relatively lower intensity need to have a very rapid rise time (that is, duration from zero energy to peak energy) for the startle response to be elicited (e.g., Graham, 1975).

Repeated, random exposure leads to habituation—namely, a diminished physiological and motor response to the stimulus—within as few as two to six presentations (e.g., Brown, et al., 1991). While two brief startle-inducing acoustic stimuli occurring within a few milliseconds of each other may lead to a greater startle response than one occurring on its own, if the first of those stimuli, referred to as the *prepulse*, is at an intensity that would not on its own elicit a startle response, then the magnitude of the startle response to the ensuing startle stimulus is reduced; a phenomenon known as *prepulse inhibition* (e.g., Davis, 1984).

Aversive states or environments may increase the startle response (see Grillon & Baas, 2003). More generally, the magnitude of the startle response can be increased in the presence of stimuli or environments with which the participant has learned to associate fear, or negative emotion (e.g., Grillon & Davis, 1997). The mere threat of an aversive stimulus evokes this *fear-potentiated-startle-response* (Baas et al., 2002).

Given the fast-acting and involuntary responses associated with startle, it is clear that it has the potential to disrupt ongoing activity and perceptual/cognitive processing (Graham, 1975; Landis & Hunt, 1939) in laboratory tasks as well as in everyday settings as revealed by air accident investigations, as well as in anecdotal evidence from pilots (e.g., Landman, Groen, van Paassen, Bronkhurst, & Mulder, 2017).

When the startle stimulus is task-irrelevant and does not require any response within the task setting the effects can be shown to diminish with repetition and be restored by rest. Rifle aiming error increased as a result of irrelevant startle stimuli. This effect reduced over the first few startle trials, and 15 minutes rest between testing sessions did not restore the degree of disruption. The reduction in startle disruption found within a single testing session was still present after a 24-hour delay and reactivity to startle had returned to initial levels after a break of a week. In addition, a forewarning had a great beneficial effect (reducing startle by as much as 60%; Foss, Ison, Torre, & Wansack, 1989a, b)

These studies reveal the clear potential for startling sounds to disrupt ongoing performance, although the detailed constellation of effects is not straightforward.

Temporary Threshold Shift (TTS). Typical startle stimuli can lead to noise-induced hearing loss, known as a TTS: formally, a reversible increase of 10dB or more in hearing threshold.

Noise containing energy in the range 2,000-6,000Hz appears to produce greater TTS than from elsewhere within the audible range (e.g., Miani, Bertino, Francescato, di Prampero, & Staffiieri, 1996). With noise above 80dB, TTS is greatest at the same frequency as the exposed noise, but at higher intensities greatest TTS is half an octave higher (e.g., Ordoñez & Hammershøi, 2011). There is also evidence that the degree of TTS may be increased by ambient heat (Chen, Dai, Sun, Lin, & Juang, 2007), as well as exercise (Miani et al., 1996). These latter effects accord with evidence of a metabolic basis for TTS (e.g., Poirrier, Pincemail, Van Den Ackerveken, Lefebvre, & Malgrange, 2010).

So, sudden loud noises impair performance, both through the physiological effects of startle and through temporary deafness that flows from a TTS.

Low Intensity Sound

Broadly, the levels of sound considered in this section are those that are commonly present in many environments, such as human voices and other natural sounds, as well as the sort of low intensity sound produced by commonly-used machinery and equipment.

Intermittent and Unexpected Sound Stimuli. Unexpected changes to an auditory task are accompanied by disruption to performance, typically by slowing response times to target stimuli, although accuracy may also be impaired (e.g., Parmentier, 2014). This can be studied using an *oddball*, or deviant auditory event that violates the foregoing pattern of sounds. These oddball stimuli can occur within but be irrelevant to, the focal task (e.g., Berti, 2008). For example, a tone is presented every few seconds that requires a judgment of its duration (‘long’ or ‘short’). Regardless of length, the majority of tones (e.g., 80%) will be at the same pitch, but occasionally the tone will be at a different pitch. Even though the pitch of the tone is irrelevant, an isolated change of pitch slows subsequent judgments of duration (see also Li, et al., 2013).

The same pattern of distraction can be observed when the sound is unattended, and the primary task involves focusing on visual information. Examples include monitoring each of a sequence of visual digits on which an odd/even judgment is made (e.g., Ljungberg & Parmentier, 2012) and tasks involving short-term memory for sequences of words (e.g., Ljungberg, Parmentier, Hughes, Macken, & Jones, 2012). In sum, across a broad range of primary tasks significant oddball effects are found whether the unexpected change is in intensity, frequency, location or identity (see e.g., Parmentier, 2014). Similar effects can be found in other sense modalities, for example with unexpected low intensity tactile events, delivered via a vibrating handle, while the participant is engaged in a visual digit categorization task (Parmentier, Ljungberg, Elsley, & Lindkvist, 2011).

Odd-ball stimuli disrupt not so much because they are rare or novel, but rather that they are unexpected or unpredictable. Novelty, rarity and unexpectedness are often correlated, but they are not the same thing: The appearance of Halley’s Comet in the sky is a very rare but also very predictable event. In order to distract, a novel or a rare sound must deviate from expectations or predictions built up from prior experience (e.g., Vachon, Hughes & Jones, 2012).

One interpretation of oddball effects is that an adaptive mechanism is at work that globally suppresses motor activity in order to interrupt the ongoing task to allow for reappraisal in the face of the unexpected event (e.g., Wessel & Aron, 2013). An alternative interpretation is that distraction is caused by the time cost associated with attention being drawn away from the primary task in order to analyze the unexpected event, before it can be re-directed to the task at hand (Parmentier, Elford, Escera, Andrés & SanMiguel, 2008).

The generality of the deviant effect is consistent with the idea that it reveals fundamental adaptive features of our auditory perception and cognition that will have material consequences for efficiency in a real-world setting.

Distracting effects of ongoing background sound. Continuous, or nearly continuous sounds produce a distinct pattern of distraction. Research has centered on focal tasks that involve either serial order or comprehension, both of which are known to contribute to situational awareness in real-world settings (Tremblay, 2004).

Serial memory. Typically, processing of order is studied via a serial recall task in which a short series of verbal items is presented with the requirement to reproduce, after a brief interval, the items in their original order. Participants are asked to ignore any sound they hear. Typical loss of efficiency due to irrelevant speech is 30-50% (Ellermeier & Zimmer, 1997; Banbury, et al., 2001). This drop in performance occurs whether the sound is restricted to sequence presentation or during to the retention interval after the sequence has been presented (e.g., Miles, et al., 1991).

In this setting the following factors are *not* associated with disruption: predictability (Jones, et al., 1992), duration of exposure (within, Ellermeier & Zimmer, 1997 or across testing sessions, Hellbrück, Kuwano & Namba, 1996), change in intensity of the sound (up to 70dB(A), Colle, 1980), degree of meaning (e.g., Jones, Miles & Page, 1990) and the similarity of task-irrelevant and the task-relevant to-be-remembered words

(Buchner, et al., 1996).

Verbal and nonverbal sounds produce broadly equivalent distraction effects. For instance, to the naïve listener, so-called *sine wave speech* sounds like a series of modulated whistles (see for example, Rosen & Hui, 2015). However, if prompted by a hint about the identity of the sound, people are able to clearly perceive the sound as speech, even though the physical signal has not changed (Tremblay, Nicholls, Alford & Jones, 2000).

Indeed, it turns out that background sound as simple as a series of two repeatedly alternating short tones is sufficient to produce distraction. Studies of the limiting conditions of the effect suggest that necessary conditions are that the sound is segmentable (i.e., is made up of separable entities, be they words, syllable, tones, etc.) and each is different from the one preceding it. Segmentation may occur due to silent gaps in the sound, or - if the sound is continuous - through very rapid changes in the physical character of the sound. Acoustic sources that comprise a repetition of the same item (e.g., a tone, or syllable) or an uninterrupted, un-segmented sound (e.g., a continuous tone or noise), even if that continuous sound varies in frequency, for example, have no (or negligible) detrimental effect on serial recall (e.g., Salamé & Baddeley, 1986). The nature of the task being used is very important however: only tasks that require processing of the relevant material in order to process its sequential properties make it susceptible to distraction (Macken, Tremblay, Alford & Jones, 1999).

The role of meaning. As we just noted, when the focal task comprises the processing of order, meaning—be it the meaning of the sound, or the relation in meaning between the sound and the focal task—is immaterial to its ability to distract. However, the situation is different when the focal task involves meaning, as for example in reading.

Here, distraction is greater in the presence of speech than non-speech sounds. For instance, a test of comprehension of a short passage revealed that several types of verbal irrelevant sound—unrelated continuous narrative, or the passage's content re-arranged randomly—produced worse disruption than instrumental music, random tones, or continuous white noise (see e.g., Martin, Wogalter & Forlano, 1988).

The effect of meaning is easy to demonstrate with memory for lists when the items are meaningful and the retrieval of the list can take place in any order. For example, lists comprising a single semantic category (e.g., names of fruit) presented visually were heard in irrelevant sound that could be the same or different from the list item category. Both types of sound led to poorer recall of the list, but background speech with related words was more distracting than unrelated, causing an additional increase in errors of about 5-10% (see Beaman, 2004).

Up until very recently, effects of auditory distraction in memory tasks have been examined with procedures that minimize participants' control over their own memory processes (see Beaman, Hanczakowski & Jones, 2014). Indeed, surprisingly little attention has been paid to the conscious control that individuals exercise over their memory performance in the presence of distraction. These so-called metacognitive control factors are known to affect memory performance appreciably. Although auditory distraction impairs memory performance in tasks minimizing participants' metacognitive control (a forced-report recognition test) when distraction is allowed of whether and how to respond (by the use of free-report of word-lists), auditory distraction impacts upon how individuals evaluate how well they have done. Participants were less accurate in judgments of their own performance, less confident in the accuracy of their performance and the likelihood of not providing reporting a word at all was increased (see also, Beaman, Hanczakowski, Hodgetts, Marsh & Jones; 2013).

Taken together these studies demonstrate that another key basic function of cognition necessary to sustain appropriate, adaptive behavior—the ability to analyze the meaning of the information in the environment—is impaired in the presence of task-irrelevant, background speech, but unlike for serial recall where physical change is the important factor. In every case, this distraction is obligatory, that is, outside the control of the individual.

Simulations of real-world settings. Using a more realistic task Perham, Banbury and Jones (2007) used lists comprising station names, departure/arrival times and amenities that related to a fictional journey. All types of retrieval strategy—in order, in any order or by category (e.g. station names)—were more error prone in background office speech. While the effect on serial recall is unsurprising, an equivalent effect on free recall is surprising in the light of some of the findings above. However, it appears that, even though they were permitted to recall in any order, participants tended to adopt a serial approach to the task anyway.

Activities more representative of office activities—text recall and mental arithmetic—undertaken with physical office sounds (printers, typing, telephones, etc.) and office noise with speech are disrupted by sound containing speech, even if the speech is meaningless. This may have been because participants were required to recall the passages verbatim and therefore will have had to adopt a serial order processing strategy, again highlighting the role of processing strategy adopted by the person rather than that assumed by the experimenter. Mental arithmetic (involving sequentially presented numbers and operators and keeping a running tally), on the other hand was disrupted by all sounds (Banbury & Berry, 1998)

Similarly, testing recall of both verbatim and gist aspects of a short lecture showed disruptive effects of a background speech and laughter only for memory of verbatim aspects of the content with memory for the gist being immune to distraction. However, if the background sound was made surprising, by having excerpts of speech and laughter interspersed in a random, rather than a coherent way, then gist memory too became disrupted. Again, this suggests that different types of distraction process may impact on different aspects of performance in complex settings (Zeamer & Fox Tree, 2013).

A realistic simulation of radar tracking was used to investigate the interaction between interruptions and distractions (Hodgetts, Vachon, & Tremblay, 2014). At unpredictable points in simulation, the screen went blank and this prompted status report requests. While background sound had no effect on performance measures before the interruption occurred, times to make a decision (as well as resume normal operations) were longer if the task interruption took place in the presence of speech related to an emergency than in quiet.

Distraction depends the precise combination of sound and task characteristics. If the key function being tapped by the task is order then the mere presence of a sound sequence is enough. But when tasks call upon analysis of the meaning of the task-relevant material, then meaningful and related sounds will have greater distracting power.

Distraction for the Ear: Routes to Mitigation

High intensity, sudden sound bursts elicit a startle reflex comprising physiological, motor, cognitive and perceptual effects. Expression of these effects depends very much on context, so that performance may even be enhanced. Ear defenders are an effective way of mitigating effects of high intensity sound. Pre-exposure is unlikely to provide a viable broadly applicable mitigation approach to reduce the effects of startle.

Increased hearing thresholds—TTSs—from loud bursts depend on a range of contextual factors but even when quite marked it may not contribute significantly to operational effectiveness. Given that the disruptive effects associated with TTS are due to physiological processes involving oxidative stress in the auditory sense organs, interventions that reduce the impact of such oxidative stress may provide some protection.

Mitigating low intensity sounds requires a different approach to that adopted for high intensity primarily because the effects arise even when the intensity of sounds is very low, not much above the threshold of audibility. Given that the physical properties (e.g., intensity, frequency) *per se* do not appear to be primary determinants of the distracting effects, targeted filtering of particular aspects of the sound is unlikely to provide an effective prevention either. However, based on the research findings reviewed above, a number of themes emerge that are worth considering.

Low intensity infrequent and unexpected changes in task irrelevant sound ‘capture attention’ but the degree of engagement in the focal task can reduce susceptibility. First, in the case of oddball sounds the addition of more random variation into the overall auditory environment may have the effect of reducing the distracting potency of any individual abrupt event (Chen & Sussman, 2013). Second, with continuous sound masking may be useful, as illustrated by the effect of ‘babble’ where a mixture of many voices is less disruptive than one or two (e.g., Hellbrück & Kilcher, 1993).

Third, there are indications that any factor that serves to maintain attention on the primary task information should reduce capture. So, interpolating an abrupt visual stimulus, at the target location, between the occurrence of the distracting sound and the target visual information served to restore response time to the target to that found in the presence of a standard sound (Parmentier et al., 2008). Promoting greater engagement with the task by making it more difficult has been shown to reduce distraction (Hughes, et al., 2013 but see Parmentier, Elford, Escera, Andres & San Miguel, 2008).

More or less continuous sounds at low intensities without isolated changes disrupt performance in visual, usually cognitive, tasks but this depends critically on the nature of the cognitive processes required to accomplish the task. There is very little evidence that this disruption can be brought under the control of the individual. In comparison to the general distracting effects of unexpected sound, continuous sound appears to be more task, or function specific. Detailed analysis of the vulnerability of these processes in ‘real world’ operational settings may be necessary in order to assess the impact and identify specific mitigation approaches, on a task-by-task basis.

KEY POINTS (see also Table 2)

1. One person’s distraction is another person’s vital information. The word ‘distraction’ invites a pejorative viewpoint, but it is worth repeating that the meaning is very much context specific. Indeed, we have skirted issues about settings in the evidence we have amassed that could be used malevolently. Nevertheless it remains the case that our

approach has been to promote an understanding of the phenomena along with some theoretical background in order to promote intelligent application of knowledge to bring about an outcome in a practical setting. Indeed, it ill-behoves us to pre-judge what such a practical setting might be, perhaps not even ones conceived of yet.

2. Perhaps the most striking theme that emerges from our overview of distraction to the eye and ear is the sheer variety and complexity of ways in which the effects of unwanted events can bring about changes to task performance. They vary from the simply crass, in which the sense organ is dealt a temporary knock-out blow and is broadly proportional to the energy being delivered to the sense organ, through to an impairment or registration or organization in the perceptual system that can be understood by some principle of proximity, or similarity, and ultimately to a variegated set of effects whose influence transcends the sense organ and may more properly be regarded as ‘cognitive’. Of course, we must be aware also that we may simply be making a *category error* inasmuch as we have scooped up a variety of phenomena that really should not have any intrinsic kinship but remain surprised when they do not.

3. While the focus here has been on basic physiological, perceptual, cognitive and behavioral levels, what research there is shows that predictions based on laboratory studies do not always provide a clear and complete picture of how distracting effects play out in such complex settings. Another issue relates to the paucity of evidence (at least in the public domain) on the detailed pattern of effects of high intensity, deliberately aversive stimuli on human performance. Emphasis has been on preventing harm, much less research has been conducted (for obvious reasons) to understand precisely the limits and extent of their effectiveness in achieving operational goals. In making predictions about real-world effects of high intensity stimuli, the nature, degree and duration of their effects is subject to many

factors relating both to the overall environment within which they occur (e.g., how dark or light it is, whether other stressors are present) as well as the current state of the operator (e.g., baseline sensory thresholds, workload, fear/anxiety). As such, it is difficult to make precise generalized predictions about detailed aspects of such distraction.

4. The review has highlighted that inefficiency may be caused by low (often very low) intensity distractors to the extent that operators may not become aware that their performance is being affected by the presence of task-irrelevant stimuli. This general finding also means that a broad understanding of the risks of distraction in a given setting will require a detailed consideration of all potential sources of distraction in the setting (effectively, any task-irrelevant stimulus) as well as detailed consideration of the components of the goal-relevant tasks that may be susceptible.

Table 1: Summary of key factors influencing distraction

THE EYE

KEY FACTORS

- Intense light
    - Flash blindness
    - Flicker
    - Chromatic flicker
    - Flashing and change blindness
- Object attentional capture
- Identifying targets
    - Effects of and on cognition
- Changes in background texture
- Simulations of real-world settings

ROUTES TO MITIGATION

High intensity light

- Reduce contrast of light source with background
- Reduce proximity of distractor to target visual information

Lower intensity light

- Reduce overlap of visual features
- Reduction of semantic salience may help
- Reduce diversity of distracting stimuli
- Reduce number of distracting stimuli
- Increase predictability of target (temporal and spatial)
- Reduce work-load
- Make target and irrelevant stimuli more distinct one from another.

THE EAR

KEY FACTORS

- High intensity sound
    - Startle
    - Temporary Threshold Shift
    - Intermittent and Unexpected Sound

Ongoing Background Sound

- The role of physical change
- The role of meaning
- Simulations of real-world settings

ROUTES TO MITIGATION

Effects of bursts

- Ear defenders
- Pre-exposure unlikely to mitigate
- Reduce individual’s exposure to oxidative stress

Low intensity sound

- No particular frequency more damaging to performance
- Infrequent and unexpected changes capture attention
- Increased overall variation may reduce impact of individual sounds
- Introduce ‘babble’ to mask individual sounds
- Increased task engagement reduces distraction

Table 2: Overall Conclusions

- Distraction due to the physical properties of stimuli is complex and requires an understanding of an array of underpinning sensory mechanisms

- Distraction is at least in part defined by the context: Prevailing mental activity determines the degree to which physical features play a role

- The portfolio of evidence is incomplete, making detailed prediction (especially in complex settings) difficult

- Low intensity stimuli produce significant impairment, of which the individual may be unaware

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