**Naturalistic Decision Making:** Taking a (cognitive) Step Back to Take Two Steps Forward in Understanding Experience Based Decisions

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**Abstract**

The field of naturalistic decision making research has hugely advanced understanding of how experts make decisions in operational environments.However, there is still a drive to improve the credibility and transferability of such research. In the current work four studies are presented which used similar methods. Standardised measures of cognitive function were administered to Authorised Firearms Officers (AFOs) after completion of immersive tactical training scenarios. The tests were chosen to examine differences between information modalities (e.g. visual vs. phonological). Results indicate that the demand associated with tactical training scenarios led to cognitive adaptions, resulting in significant increase in visual processing capacity and reductions in phonological processing capacity. The findings indicate that an adaptive switch to visual information modality may underpin experience-based decision making by AFOs. The findings provide insight into why training and policy should keep verbal and auditory demands placed on AFOs to a minimum.

**Key words: Naturalistic Decision Making, Police, Firearms, Cognition**

**General audience summary**

Historically, the way people make decisions was examined from an idealistic point of view, not capturing the factors impacting decision making such as time pressures, incomplete information, ambiguity, and a limited resource capacity. Naturalistic Decision Making (NDM) research proposes that in the real world, expert decision makers overcome these issues by using prior experience to guide decision in a faster, more intuitive fashion. The current research used standardised cognitive tests to examine whether modality specific information (e.g. visual or verbal) processing differences are observed in experts when making decisions in naturalistic environments. Four studies were conducted that examined the processing capacity of Authorised Firearms Officers (AFOs) as they completed highly realistic tactical training scenarios. The studies revealed that the visual processing capacity of AFOs increased, whilst the verbal processing capacity (speaking and listening) simultaneously decreased. This indicated that AFOs have less capacity to process verbal information, such as listening and talking which supported previous research demonstrating that the communications strategies of operators in naturalistic environments becomes more simplistic as demand increases. However, AFOs simultaneously have increased capacity to process visual information, to inform their situation awareness of the environment, potentially to facilitate threat assessments. All AFOs in the current study made appropriate tactical decisions; therefore, the current work provides insight into the at-the-time cognitive capacities of AFOs when operating effectively in highly demanding contexts. This work can inform the training and policy requirements of AFOS, suggesting that verbal communications (speaking and listening) should be minimised where possible.

Naturalistic Decision Making (NDM) is characterised by uncertain, dynamic environments, ill-structured problems, competing goals, data overload, and time constraints (Gore, Flin, Stanton, & Wong, 2015; Klein, Ross, Moon, Klein, Hoffman, & Hollnagel, 2003; Klein, 2015). When operating in demanding contexts there is potential for cognitive overload, resulting in decrements to attentional resources available for perception and decision-making (Baddeley, 2000; Barulli, & Stern, 2013; Sliwinski, Smyth, Hofer, & Stawski 2006). Cognitive capacity limitations have been demonstrated to impact decision making in many settings including treatment implementation by patients with heart failure (Dickson, Tkas, & Riegel, 2007); interaction with automation when driving (Young & Stanton, 2002), utilisation of mobile technologies (Oulasvirta, Tamminen, Roto, & Kuorelahti, 2005), and weapon discharge by police officers (Kleider & Parrott, 2009). However, such research was not conducted in naturalistic environments or did not examine expert decision makers, which are essential constituents of NDM theory (Klein, 2015). Expert decision makers overcome capacity issues via use of cognitive strategies allowing natural cognitive storage limits to be circumvented (Ward, Farrow, & Williams, 2008). The NDM field has promoted understanding of the different strategies, heuristics and adaptive processes used to cope with and make decisions in high stakes naturalistic environments (Endsley & Garland, 2000; Klein, 1997; 2008; 2015; Lipshitz, Lipshitz, Klein, Orasanu & Salas, 2001).

**Working Memory**

In the UK, an Authorised Firearms Officer (AFO) is a police officer certified to carry and use firearms, operating in teams of at least 2-4 officers. Errors in tactical decision making by police officers have been attributed to reduced Working Memory (WM) capacity (Kleider & Parrott, 2009). WM is a limited capacity cognitive system, responsible for the active maintenance and manipulation of task relevant information. It acts as an interface between the external environment, internal memory constructs, and action (Baddeley, 2000; Miyake & Shah, 1999). A prominent behavioural model of WM proposes a modality-free controlling central executive, two modality specific subsidiary slave systems (phonological and visuospatial) for the temporary storage of information (Baddeley, 2000). This model is criticised for neglecting other sensory inputs (e.g. olfactory and somato-sensory) and some of its accounts of functionality, debate that is outside the scope of the current research (Miyake & Shah, 1999). However, this model provides a sound basis for examining the modality specific aspects of WM.

Decision making in naturalistic environments relies on experience-based pattern matching, a key challenge for decision makers is making sense of the conditions rather than choosing between multiple options (Klein, 2015). Situational Awareness (SA) requires the use of environmental cues to generate a perceptual map of an incident to inform decision-making and action. WM is crucial for adequate SA, particularly in directing attention to critical information or cues (Endsley, 1997). An experienced police officer will pay varying levels of attention to SA elements in an encounter based upon assessment of their relative importance to basic survival/ threat assessment (Page, Thibeault, Page, & Lewinski, 2008; Shomstein & Yantis, 2004). Malleable Attentional Resources Theory (MART) proposes that attentional resources are not fixed, rather they are flexible pools that shrink and expand (within bounds) depending on current demand (Young & Stanton, 2002). Measuring WM processes in naturalistic environments could promote understanding of which information modalities are most prevalently used by experts across different domains (Brewer, Ball, & Ware, 2016).

In teams, decision-making relies upon good teamwork and communication (Stanton, 2011). Communication does not just provide insight into team cognition; it actually represents cognitive processing at the level of the team (Cooke, Gorman, & Kiekel, 2008). Teamwork processes such as verbal communication can become the limiting factor in determining the workload of the team, rather than the work itself (Carletta, Anderson, & McEwan, 2000; Driskell, Salas, & Driskell, 2017; Salas & Cannon-Bowers, 2001). The phonological loop is assumed to have evolved for the production (and maintenance) of complex language essential for verbal communication (Christiansen & Kirby, 2003). Research examining verbal communication in a jet cockpit; found that verbal language use differed depending on the abnormality of a flight simulation (Sexton & Helmreich, 2000). Communication failures between flight crew outweigh technical difficulties as a primary cause of aviation accidents (Connell, 1995; Kanki, 1995). During highly demanding situations surgeons tend to reduce communication/language complexity with their team, whilst visual attention is maintained (Wetzel, Kneebone, & Woloshynowych, 2006). The visuospatial processing system is the most dominantly used modality in situations of threat or high demand (Liddell et al., 2005). The completion of visual search tasks is usually improved as a result of increased physiological arousal, even to excessively high levels (Lambourne & Tomporowiski, 2010). Attentional focusing ensures that emotionally salient features from complex environments are preferentially processed, in high-risk environments this will likely be visually based threat cues, such as the presence of a weapon (LaBar & Cabeza, 2006).

**Modality Specific Cognitive Adaptions**

A key question for naturalistic decision making is how cognition adapts to complexity (Gore et al., 2015). Excessive physical, cognitive, and emotional demand can result in physiological changes, or adaptions, to facilitate coping with demand (Goldstein, 2001; McEwen, 2000). The primary (measurable) effects of increased physiological arousal include elevations in heart rate, pupil size, and core temperature (Charmandari, Tsigos, & Chrousos, 2005). Physiological arousal induced by cognitive, physical, and emotional demand has been demonstrated to impact upon police officers’ decision making (Hoing & Lewinski, 2008; Kleider & Parrott, 2009; Vrij & Dingemans, 1996;). A heightened physiological response can result in improved cognition and focused attention, although this is achieved by neuro-physiological changes that actually reduce cognitive capacity (Charmandari et al., 2005; Hoing & Lewinski, 2008; Sliwinski et al., 2006). Stress hormone administration to particular brain regions has been demonstrated to impair WM task performance (LaBar & Cabeza, 2006).

In the UK, AFOs are encouraged to use the National Decision Model (previously Conflict Management Model), this requires the officer to gather information and assess threat to guide decision-making (ACPO, 2013). This requires officers to communicate with higher command, their colleagues, potential suspects, and civilians but perhaps more critically to visually scan the environment for potential threats (e.g. presence of a weapon) enabling adequate SA development. A study into the shooting behaviour of novice (student) trainees found that decisions concerning weapon discharge relied on WM capacity (Brewer et al., 2016). Brewer and his colleagues suggest future research should contrast different information processing modalities (e.g. visual vs. phonological) as predictors of quick decision-making. However, such questions need to be examined with ecological validity to offer insight into NDM, which is an aim of the current work.

NDM research has been criticised for lacking formalisation of constructs and clear defining measurable parameters (Thomson, Lebiere, Anderson, & Staszewski, 2015; Todd & Gigenrenzer, 2001). Whilst the qualitative understanding provided by NDM methods (e.g. cognitive task analysis) can offer valuable insight into the intuitive decision making process (Klein, 1993; McAndrew & Gore, 2013). The findings can be problematic due to the adaptive functionality of recall to enhance fitness rather than accurate recall (Suddendorf & Henry, 2013) and that frequently expert decision makers differ in their accounts of the decision making process (Shanteau, 2015). In addition, evaluating decision making retrospectively may reduce understanding of how the state of an operator effects cognition at the time decisions are made (Ask, & Granhag, 2007; Macquet & Skalej, 2015). A key contribution of NDM is the use of ecologically valid methods for understanding decision making (Lipshitz, Klein, & Carroll, 2006), however there is still a drive to improve the credibility and transferability of methods used in the NDM field (McAndrew, & Gore 2013). The aim of the current research is to examine the at-the-time modality specific cognitive capacities of expert decision makers operating in high fidelity training environments, using standardised cognitive tests. Providing a body of work with reliable, measurable parameters and good ecological validity in keeping with NDM research.

In the current work, four studies will examine the cognitive function of AFOs participating in high fidelity tactical firearms scenarios. Three primary hypotheses included:

1. The demands of tactical training will result in AFOs experiencing physiological arousal. This shall be reflected by significant increases in heart rate and temperature.
2. The psychophysiological demands placed on AFOs will alter cognitive function. This shall be reflected by significant differences in cognitive task performance
3. The precise changes to cognitive function will differ depending on the information modality (e.g. visual vs. phonological) and demand (e.g. executive vs. non-executive).

**Method**

**Participants**

The tactical training of AFOs was attended where participants were opportunistically recruited on voluntary basis. A total of 29 participants took part in study 1, 28 in study 2, 24 in study 3, and 19 in study 4. Both male and female AFOs of various ages ranging from 21–55 years old participated. The exact demographic information presented is limited in order to protect the confidentiality of participants involved, although it is a representative sample of AFOs. All participants had at least the minimum level of training required to be an operational AFO. The ethics committee of Liverpool University approved the study and all subjects gave their written informed consent prior to taking part.

**Design**

In all four studies, a one factor repeated measures design was used. Time was the independent variable (2 levels), in relation to completion of the final assessment scenario. The dependant variables included measures of heart rate, temperature, and cognitive test performance.

**Equipment and Materials**

The materials and equipment chosen were required to be used at the tactical training of AFOs, so were required to be highly portable and durable. The primary (measurable) effects of increased physiological arousal include elevations in heart rate, blood pressure, and core temperature (Charmandari et al., 2005; Sliwinski et al., 2006). An Omron R7 digital automatic blood pressure monitor measured heart rate (Beats Per Min, BPM) and a Braun Thermo-scan ear thermometer measured core temperature (0c). The collection of data within a police setting is notoriously difficult due to restricted access, data protection issues, and authorisation procedures, particularly when firearms are present. The time restrictions placed on AFO training was great, therefore all testing had to be quick (20 min testing windows) and efficient but still have good validity and high reliability as measures of particular cognitive function (Basso, Carona, Lowery, & Axelrod, 2002; Rabin, Barr, & Burton, 2005; Strauss, Sherman, & Spreen, 2006). The cognitive and physiological adaptations resulting from increased demand may start to reduce once the stimuli(s) causing the demand has been removed (Lewinski, 2008). This provided further rationale for short testing windows.

A battery of cognitive tests with the highest internal validity (i.e. standardised and replicable), shortest administration time was selected. The tasks chosen for use in study 1 were the Digits Forward task (DF), Digits Backward task (DB), and the Symbol Search task (SS). In study 2 the Trail Making Task (TMT), parts A and B were used along with the Letter Number Sequencing Task (LNS). In study 3, the Corsi Block Tapping task (CBT) task was used and in study 4, the Self Ordered Pointing Task (SOPT) was used. Paper versions of sub-tests were taken from the Wechsler Adult intelligence scale v.3 (Wechsler, 1981), including the DF, DB, LNS, and the SS tasks. Test sheets and instructions came from the updated WAIS III version of the testing battery (The Psychological Corporation, 2002). The SS testing sheets, taken from the WAIS III were split in two and completion time was halved (60 to 30 Ss) to avoid repetition effects and reduce testing time. The TMT (A and B) was also used (Reitan, 1992). Test sheets were taken from the Halstead-Reitan test battery (1962). An electronic version of the CBT (Corsi, 1972) and the self-ordered pointing task (Petrides & Milner, 1982) were used. The tests were run using four Toshiba L42 laptops. The software and scripts used for running the tests were provided by Inquisit tm (Millisecond Corporation, 2002). A Micronta (Model 63-9190) digital sports timer was used to time completion on relevant tasks.

**Cognitive test selection rationale** was an important consideration as all test were selected to examine particular cognitive capacities. The digit span tasks examine the capacity of the phonological loop, requiring the active maintenance of verbal information (Baddeley, 1992). The underlying processes underpinning the DF and DB though generally similar may differ slightly (Reynolds, 1997). The DF represents a purer measure of phonological active maintenance and the attention processes recruited for rehearsal (Conklin, 2000). Strong correlations have been demonstrated between sub-component tasks involving the manipulation of material (e.g. DB and LNS) and tasks of general executive function which involve the manipulation of additional stimuli to that being stored (Oberurer, 2000).

The SS and TMT part A both examine the visual processing speed/scanning function of individuals as the tasks require the pattern matching and searching of visual stimuli respectively. The executive demand of both tasks is minimal (Crowe, 2000). The SS task requires individuals to examine visually presented patterns and examine whether they are similar or dissimilar to target patterns, task completion relies on the visuospatial sketchpad (Thomason et al., 2008). Both parts of the TMT task require the visual tracking of a phonological sequence, although task B also requires executive control to switch between sequences and inhibit inappropriate responses (Groff & Hubble, 1981; Lezak, 1995). The correlation in performance between TMT A and B is high (r = .64), highlighting that common factors underpin performance in both tasks (Sanchez-Cubillo et al., 2009). Processing speed has been demonstrated to account for 40% of the variance observed in tasks of executive functioning which require visual search processes (Nelson, Nelson, Yoash-Gantz, Pickett, & Campbell, 2009).

Tasks that require the phonological loop typically lead to activation of the left hemisphere, in particular the left posterior cortical (parietal lobe) and supplementary motor regions (Broca’s area). These areas are the anatomical location of the phonological store and the articulatory loop respectively. The DF, DB, LNS, and TMT have all been demonstrated to lead to activation of these brain regions (Haut et al., 2000; Hoshi, 2000; Kosslyn, 1993; Smith & Jonides, 1999; Zackzanis, Mraz, & Graham, 2005). The neurological locations active during performance of the LNS are the same as during the DB (Haut et al., 2000). The DB and LNS also lead to activation of the right anterior occipital cortex and numerous other higher and lower visual processing areas. Activation of such areas reflects a strategy of visualization when manipulating the letter and number strings (Conklin, 2000; Hoshi, 2000; Kosslyn, 1993). The DB, TMT (B), and LNS have also been associated with activation of the dorsolateral prefrontal cortex (DLPFC) region (Hoshi, 2000; Zackzanis, Mraz, & Graham, 2005) an area of the brain which is associated with the completion of tasks involving executive cognitive function. Activation of the DLPFC and posterior regions during the TMT B is predominantly associated with being in the left hemisphere, demonstrating the primary verbal nature of this task (Zackzanis et al., 2005). The SS task leads to increased activation of areas associated with visuospatial processing (e.g. medial occipital and occipital-parietal regions), the neurological locations associated with the visuospatial sketchpad (Farah, 1988; Hanley, Young, & Pearson, 1993). Greater activity of the left DLPFC was associated with decreased performance in this task, suggesting participants were inappropriately employing a phonological strategy for a simple visual processing task (Sweet, Dorph-Petersen, & Lewis, 2005).

The CBT is a visual task involving minimal executive demand (Corsi, 1972; The Psychological Corporation, 1997; Wechsler, 1981). It is a test primarily employed for the assessment of non-verbal WM (Spinnler, Della Salla, Bandera, & Baddeley, 1988). The executive demand of the task is minimal as no manipulation of the material is required, information is only stored and maintained. The CBT is commonly viewed as the visuospatial equivalent of the verbal DF task (Strauss et al., 2006). The SOPT is a visual task that requires executive control for adequate task completion (Petrides & Milner, 1982; Ross, Hanouskova, Kat, Calhoun, & Tucker, 2007). Impairment in both tasks was most pronounced in individuals with right hemispheric damage, in areas believed to be the neurological location of the visuospatial sketchpad. This was further evidenced by the location of brain lesions that lead to decreased visual span performance (Kessels et al., 2000). Posterior activation during completion of the CBT tends to be greater in the dorsal regions of the right parietal and occipital lobes. This suggests the task primarily requires the active maintenance of spatial information although there is considerable overlap between the two systems (Kessels et al., 2000; LaBar, Gitelman, Parrish, & Mesulam, 1999). Neuro-imaging studies have revealed that completion of the SOPT leads to activation of the DLPFC and areas associated with the completion of executive tasks (Petrides, 2000). The SOPT is highly correlated with performance on the spatial span tasks and other primarily visuospatial tasks demonstrating that this is the dominant process employed (Ross et al., 2007, Roth & Baribeau, 1996). A visual task which requires executive control for adequate task completion (Petrides & Milner, 1982; Ross et al., 2007).

**The simulations** were part of the final assessment exercises of AFOs completing compulsory refresher training on a number of core competencies. Due to security issues, it was not possible to collect data regarding the tactical decision making of the AFOs. However, the scenarios were the final test of a summative assessment week. Trainers and examiners were continuously monitoring the tactical decision making of the AFOs. If at any point, the decision making of an AFO were deemed inappropriate, it would have resulted in immediate assessment failure and revocation of their firearms licence. This did not happen on any occasion. Therefore, whilst the decision making of AFOs was not necessarily uniform across all teams, it was always appropriate and within tactical bounds. Due to security issues, the precise nature of the tactic and details of the final scenarios can also not be fully detailed. The tactic involved actively locating and detaining an individual who has already posed a lethal threat. Situations typically involve great time pressure (based upon a threat to life) and the area in which the tactic is completed can be extremely large. The tactic involved a faster decision making pace, (this tactic is the most cognitively demanding AFOs complete. The final assessment scenarios were designed by Subject Matter Experts (SMEs) who were AFO training leaders. A typical scenario took place in an ex-university tower block, comprising of six floors. AFO’s were informed that two armed disgruntled students were in the building shooting members of the public. AFOs were instructed to locate and detain both individual as quickly as possible whilst adhering to their training. AFO’s completed the tactic in teams of four. Six distressed role players approached the firearms officers at random points throughout each scenario, pointing the AFOs in the direction of the suspects. The average final assessment phase lasted 45 min in total.

During the completion of the assessment exercises AFOs wore the same PPE as they would operationally. This included; a Nomex/poly-cotton overall, HG2 body armour, a ballistic helmet, and load bearing vest (LBVs) containing a baton, tazer, radio equipment, and handcuffs. Officers carried the same firearms as they would operationally, depending on the tactical training package. This included a Glock 17 self-loading pistol and a Heckler and Kock G36 or an MP5 semi-automatic carbine. The only modifications to the weaponry were the fitting of SimmunitionTM kits to allow the use of SimmuntionTM rounds. For safety purposes during training events live ammunition could not be discharged from the weapons once such alterations had been made. Two types of ammunition were used by AFO’s during tactical training scenarios; SimmuntionTM secure blank (which produces a loud sound) and SimmunitionTM FX (which is a marker round using a paint pellet similar to paintball). AFO’s were issued with (and deployed) Nico 1 and 9 bang distraction devices depending on the tactical training package.

During the scenarios, individuals playing the role of suspects had extensive experience in the use of firearms and tactical deployment (in the police, military, or military simulation events). This was to present worst case scenario suspects who were prepared, trained, and posed a challenge to the AFO’s. Suspects wore realistic clothing to disguise them as the character they were asked to portray. Depending on the tactical training package suspects would carry Glock 17 self loading pistols and MP5 semi-automatic carbines and G36 rifles firing SimmunitionTM secure blank ammunition , or replica AK47 semi-automatic rifles, replica Glock 17 self-loading pistols firing Lugar 9mm blank ammunition or small plastic pellets (spring or gas propelled). The suspects were instructed to appear aggressive (both verbally and visually) and pose a threat to AFOs that required the discharge of a firearm. Role players were placed in the assessment scenarios to simulate members of the public attempting to leave an area/building in which an incident is taking place, or to act as if they have been wounded. AFOs may have to complete tactics in the presence of the public (rather than a sterile scene); therefore adding role players to a scenario creates realism. Role players received an extensive briefing and debriefing which focused on the dangers associated with tactical training. Role players were issued with PPE including eye protection, ear protection, and wore necessary specialist clothing. All role players signed consent and privacy forms, whilst being vehemently instructed not to take part if they felt uncomfortable with extremely loud bangs, flashes, or the use of weaponry.

**Procedure**

In all studies, immediately prior to their deployment to the simulation, participants selected to take part were taken individually to a quiet side room next door to the holding area. Heart rate and core temperature were recorded at this point (T1). A battery of pre-selected tests was then administered (a different battery for each study). The test presentation order of tests was counterbalanced between participants to prevent order effects. The test instructions of each test were read aloud to the participant, and when understood the task would begin. Immediately upon completion, the next task instructions were read, this continued until all tasks had been completed.

In study 1, the SST was administered. Participants were given a practice sheet and instructed that there were two target symbols and five matching symbols. If either of the target symbols was present in the match symbols set then the participant should circle yes at the end of the row of symbols. If neither of the target symbols is present in the match symbol set, then participants were instructed to circle no at the end of the row of symbols. Errors were highlighted and corrected so that participants fully understood the task. Participants were instructed they had thirty Ss to complete as many rows of symbols as possible. Once thirty Ss had elapsed participants were instructed to stop, the total number of correct items was recorded (minus incorrect items). During the DF task participants were read aloud (by experimenter using a monotonous, one S paced tone) a sequence of numbers, which they were instructed to repeat back in the same order. Participants were given three practice trials; errors were corrected so that the task was understood. Participants were instructed that as the trails progressed, the list of numbers would increase in size. The DB test was administered in exactly the same manner, except participants were instructed to repeat the numbers in reverse order. During both trials the number of correctly recited items was recorded. Total digit span score was calculated by adding each participant’s digits forward and digits backward scores from the relevant time points.

In study 2, the TMT (A) required participants to connect circles containing numbers in ascending order in the quickest time possible. Participants were presented with a practice sheet consisting of circled numbers 1-8 randomly spread. Participants were instructed not to remove their pencil from the page at any point once the test had begun, if an error was made participants were directed back to the number prior to the mistake. After completion of the practice test sheet and the task being understood the trail began, with numbers ranging from 1-25. The TMT B was administered in exactly the same fashion except in this test version the 25 circles enclosed the numbers 1-12 and letters A-K. Participants again completed a practice sheet consisting of a smaller selection of letters and numbers in circles. Participants were instructed to connect the letters and numbers in order, alternating between number and letter (beginning at 1). The time taken to complete both trails was recorded. The LNS task required participants to repeat back a mixed set of numbers and letters read aloud to them (by experimenter). Participants were instructed to re-order the sequence with numbers to be repeated first (in numerical order) followed by letters (in alphabetical order). The length of each trail increased as the test progressed. Participants completed three practice trails before the task began. The number of letter number sequences an individual accurately repeated in the correct fashion was recorded with no time limit placed on this task.

In study 3, participants were positioned in front of a laptop which contained on screen the instructions for the CBT. Participants were instructed to read the on screen instructions, which were then briefly repeated by the experimenter. Once all participants understood the task they were instructed to begin by clicking the mouse. The task presented participants with six blocks on screen; the blocks would flash in a random sequence. After each flashing sequence participants were required to repeat the sequence by clicking on the relevant blocks in the correct order. As the trials progressed the number of flashing blocks contained in the sequence increased. Participants were instructed that a small box at the bottom of the screen containing the words blank should be clicked on if there was a point within the sequence where the location of the flash could not be recalled (but it was thought a flash had occurred). This was important as it maintained the order of the sequence. Participant’s total score and span score were recorded.

The procedure for study 4 was the same, except the instructions presented on the laptop screen were for the SOPT. Participants were required to use the mouse to click on one of six pictures. Once they had done this, the six pictures on the screen would automatically jumble and participants were required to click on a different picture. This was repeated until all six pictures had been clicked upon. It was strongly reiterated to participants that they were not allowed to click on the same spatial point (after the pictures had been jumbled), more than twice in a row. The number of pictures on screen would increase as the trails progressed (6, 8, 10 and, 12 pictures). The sum of correct scores for each amount of pictures, and total score were automatically recorded. Participants then took part in the final assessment scenario. Immediately after completion of the final assessment phase the final measurements were collected (T2). In all studies, test administration was the same as for the measurements taken prior to commencement of the final assessment scenario.

**Analysis**

In all four studies repeated measures t-tests were conducted to examine the effect of participation in a highly immersive tactical simulation on cognitive test scores and physiological measures. The majority of data was normally distributed, however a few of the measures were not. The comparison of means (t values) when group sizes are equal (particularly within a repeated measures design) generally controls well for type 1 error rates, even when data is not normally distributed, homogeneity of variance is not assumed and data is skewed (Keselman, Algina & Kowalchuk, 2002; Donaldson., 1966). However, for purposes of statistical robustness, when data was not normally distributed, the non- parametric test version (of the t-test) was also reported (Z scores). No differences were noted between parametric and nonparametric test outputs of these data sets. To account for multiple comparisons, in each individual study, the Bonferroni correction method was used (α = 0.05/number of comparisons). All statistical analysis was conducted using IBM SPSS v21. 2.

**Results**

In study 1, there was a statistically significant increase in heart rate (*t*28 = 12.52, *p* < 0.01, *r* = 0.92), and temperature (*t*28 = 9.72, *p* < 0.01, *r* = 0.88) between T1 and T2 (see table 1 and figure 1). Accurate digit recall statistically significantly decreased between T1 and T2 during the digits forward task (*t*28 = 3.47, *p* < 0.01, *r* = 0.54) and digits backward task (*t*28 = 2.38, *p* < 0.05, *r* = 0.41). Total Digit recall in both components of the digit span tasks statistically significantly decreased between T1 and T2 (*t*28 = 3.63, *p* < 0.01, *r* = 0.57). Total correct symbol matches during the symbol search task statistically significantly increased (*t*28 = 3.63, *p* < 0.01, *r* = 0.57) after a training scenario (see table 1 and figure 1). In study 2, a statistically significant increase in heart rate (*t*27 = 16.23, *p* < 0.01, *r* = 0.97), and temperature (*t*27 = 6.28, *p* < 0.01, *r* = 0.77), (*z* = 4.23, *p* < 0.01) occurred between T1 and T2 (see table 1 and figure 1). Completion time of both trail making task components was affected between T1 and T2, statistically significantly decreasing during task A (*t*27 = 7.05, *p* < 0.01, *r* = 0.81) and significantly increasing during task B (*t*27 = 3.53, *p* < 0.01, *r* = 0.57). Item recall during the letter number sequencing task statistically significantly decreased (*t*27 = 4.75, *p* < 0.01, *r* = 0.68), (*z* = 3.61, *p* < 0.05) between T1 and T2 (see table 1 and figure 1).

In study 3, a statistically significant increase in heart rate (*t*23 = 9.18, *p* < 0.01, *r* = 0.89) and temperature (*t*23 = 5.52, p < 0.01, *r* = 0.75) (*z* = 3.81 *p* < 0.001) occurred between T1 and T2. Corsi-block tapping task performance statistically significantly increased between T1 and T2 for span score (*t*23 = 1.88, *p* < 0.05, *r* = 0.37), (*z* = 1.72, *p* < 0.05) and total score (*t*23 = 2.16, *p* < 0.05, *r* = 0.41). In study 4, a statistically significant increase in heart rate (*t*18 = 5.68, *p* < 0.01, *r* = 0.81) and temperature (*t*18 = 2.36, *p* < 0.05, *r* = 0.49), (*z* = 4.63, *p* < 0.05) occurred between T1 and T2. During the self-ordered pointing task a statistically significant decrease in error scores occurred between T1 and T2 for sum of 6 pictures (*t*18 = 3.70, *p* < 0.01, *r* = 0.68), (z = 2.93, p < 0.01), sum of 10 pictures (*t*18 = 2.56, *p* < 0.05, *r* = 0.51), sum of 12 pictures (*t*18 = 2.89, *p* < 0.05, *r* = 0.58), and sum of total pictures (*t*17 = 4.27, *p* < 0.01, *r* = 0.72). No statistically significant change to error scores for sum of 8 pictures (*t*16 = 1.03, NS) was observed.

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| Study 1 | Baseline | After Scenario | (t)  | Study 2 | Baseline | After Scenario | (t)  |
| HR  | 78.86 (11.57) | 118.38 (16.44) | 12.52\*\*\* | HR | 73.75 (10.75) | 118.71 (16.61) | 16.23\*\*\* |
| Temp  | 36.88 (0.45) | 37.67 (0.44) | 9.72\*\*\* | Temp | 36.74 (0.45) | 37.50 (0.54) | 6.28\*\*\*  |
| DF | 12.17 (1.79) | 11.17 (1.98) | 3.47\*\* | TMT A | 27.57 (6.92) | 19.46 (4.36) | 7.05\*\*\* |
| DB | 7.69 (2.17) | 6.83 (2.22) | 2.38\* | TMT B | 49.75 (13.56) | 58.86 (18.09) | 3.53\*\* |
| DT | 19.86 (3.53) | 18.00 (3.75) | 3.63\*\*\* | LNS | 12.64 (2.98) | 10.61 (2.35) | 4.75\*\*\*  |
| SST | 19.52 (3.47) | 23.10 (4.21) | 7.14\*\*\* | - | - | - | - |
| Study 3 |  |  |  | Study 4 |  |  |  |
| HR | 75.38 (11.72) | 111.92 (18.37) | 9.18\*\*\* | HR | 74.95 (15.90) | 98.32 (25.29) | 5.68\*\*\* |
| Temp | 36.53 (0.56) | 37.23 (0.47) | 5.52\*\*\* | Temp | 36.71 (0.57) | 37.57 ± (0.47) | 2.36\* |
| Corsi Span | 5.71 (0.91) | 6.04 (0.95) | 1.88\* | SOPT 6 | 2.58 (1.35) | 1.00 ± (1.29) | 3.70\*\* |
| Corsi Total | 48.88 (16.37) | 57.08 (19.65) | 2.16\* | SOPT 10 | 4.32 (2.00) | 2.95 ± (2.20) | 2.56\* |
| - | - | - | - | SOPT Total | 15.11 (5.15) | 10.58 ± (7.68) | 4.27\*\* |

**Table 1.**

Mean (and standard deviation) of physiology and cognitive tests at baseline and after completion of tactical training scenario

*Note*.\* p<0.05, \*\* p<.01, \*\*\*p<.001. In study 1, N =28, study 2, N = 28, study 3, N = 24, and study 4, N =19.

Fig. 1. Graphs showing mean differences in heart rate, temperature, digit span, symbol search, letter number sequencing and Corsi-block measures. *Note.* Error bars denote SE adjusted for repeated measures design.

**Discussion**

Overall, participation in an immersive tactical training simulation significantly influenced the physiology and cognitive function of AFOs. The shifts in cognitive change differed depending on the primary modality that the cognitive test assessed, therefore hypotheses one, two, and three were accepted. An assessment of physiological arousal is outside the scope of the current work. However, it can be inferred that the changes in cognitive function result from the demands of the tactical assessment scenario as increases in heart rate and temperature are positively correlated with increases in cortisol (Meyer, 2000).

**Working Memory**

The AFOs were operating in uncertain, dynamic environments, with data overload, and time constraints – it appears the impact of operating in such an environment led to cognitive adaptations to facilitate coping with demand (Gore et al., 2015; Klein, 2015). Whilst the decision making strategies of AFOs were not recorded due to security issues. The fact that all AFOs passed the training assessment indicates that the data recorded in the current studies provide insight into the cognitive state of an AFO when making appropriate tactical decisions in naturalistic environments (Ask, & Granhag, 2007; Macquet & Skalej, 2015). In computer simulation studies with experts (Kleider & Parrott, 2009) and novices (Brewer et al., 2016), errors in tactical decision making by police officers have been attributed to reduced WM capacity (Kleider & Parrott, 2009). Potentially due to cognitive overload, resulting in decrements to attentional resources available for perception and decision-making (Baddeley, 2000; Sliwinski et al., 2006). At first glance, the current work appears to support such a view. However, in the current studies, AFOs performance on certain WM tasks increased, whilst performance on others decreased. This supports the view that in operational environments expert decision makers use cognitive strategies to circumvent natural cognitive storage limits (Baddeley, 2000; Ward et al., 2008). Understanding changes in cognition can provide insight into the modality of the environmental cues used by AFOs to generate a perceptual map (SA) of an incident used to inform decision-making and action (Endsley & Garland, 2000; Endsley, 1997; Klein, 2008).

**Modality specific cognitive adaption**

The performance of AFOs on the DF, DB, and LNS tasks decreased between T1 and T2, indicating a reduction in phonological processing capacity. A heightened physiological response can result in improved cognition and focused attention, although this is achieved by neuro-physiological changes that actually reduce cognitive capacity (Charmandari et al., 2005; Hoing & Lewinski, 2008; Sliwinski et al., 2006). A primary role of the phonological loop is the production (and maintenance) of complex language essential for verbal communication (Christiansen & Kirby, 2003). Although not measured in the current study, it can be strongly inferred that the AFOs would have less capacity to listen to verbal information and to communicate using complex verbal language. In support of this, previous research has revealed significant changes in the use of language by jet cockpit crews (Sexton & Helmreich, 2000) and surgeons (Wetzel et al., 2006) operating in naturalistic environments. This typically results in a reduction in the complexity of language used (e.g. more monosyllabic and less superfluous), particularly when the operational environment becomes more demanding.

A reduced capacity to communicate has the potential to affect team cognition and decision making in naturalistic environments (Cooke et al., 2008). Communication between teams typically reduces in extreme environments and this can have a negative impact on team cognition (Salas, & Driskell, 2017). However, AFO performance across all WM tasks was exceptionally high at baseline and although performance on the phonological tasks significantly decreased, it was still maintained at exceptionally high levels in comparison to normative data samples (Iverson & Tuslky, 2002; Strauss et al., 2006). Moreover, in the current study, the reduction in phonological capacity observed did not negatively affect performance in naturalistic environments, all AFOs made appropriate tactical decisions despite the observed changes. Individuals who expend the cognitive resources necessary to speak more elaborately do so at the expense of decreased SA (Sexton & Helmreich, 2000). If reductions in phonological processing capacity result from increased demand, then training and policy developed for expert decision makers operating in highly demanding situations should restrict verbal communications to situations when it is absolutely necessary. The use of more effective language styles is trainable (Sexton & Helmreich, 2000). It has been frequently proposed that NDM by experts operating in demanding environments involves pattern recognition techniques, rather than the consideration of multiple options (Gore et al., 2015; Klein, 2008; Lipshitz et al., 2006). This may be due to experts being unwilling to waste cognitive resources verbalising multiple decision alternatives when such capacity is already limited. Instead, attention is focused on making sense of the environment and selection of appropriate environmental cues to inform adequate SA (Endsley & Garland, 2000; Klein, 2015).

Despite a reduction in phonological WM task performance, the capacity of AFOs to process visuospatial information increased. Performance on the SS, TMT (A), CBT, and SOPT improved between T1 and T2. An experienced police officer will pay varying levels of attention to SA elements in an encounter based upon assessment of their relative importance to basic survival/ threat assessment (Page et al., 2008; Shomstein & Yantis, 2004). The adequate attainment of SA by AFOs appeared to focus on perceptual cues that were primarily visuospatial in nature. In the current study, AFOs were completing high threat scenarios in which the potential for force to be used against them was high. Attentional focusing ensures that emotionally salient features of complex, threatening events are processed (LaBar & Cabeza, 2006). The modality with the greatest capacity for processing environmental cues to generate SA is visuospatial, this type of information will facilitate sense making (i.e. presence of a weapon) and decision making in line with experience and training (ACPO, 2013; Endsley & Garland, 2000; Klein, 2008; 2015).

The visuospatial processing system is the most dominantly used modality in situations of threat or high demand, as it is the most robust to psychophysiological effects (Liddell et al., 2005). The fact that all AFOs in the current study made appropriate tactical decisions indicates that NDM in such contexts relies on visuospatial information. MART proposes that attentional resources are not fixed, rather they are flexible pools that shrink and expand (within bounds) depending on current demand (Young & Stanton, 2002). The current study reveals that the size of modality specific resource pools may also contract and expand depending upon which is most critical for SA and decision-making. Measuring WM processes in naturalistic environments can promote understanding of what information modality is dominant and how this might affect SA generation, communication, and ultimately decision-making (Brewer, et al., 2016).

**Limitations and future research**

A limitation of the current work is that due to security issues, it was not possible to collect data regarding the decision making processes of AFOs. Further research should seek to examine whether changes in cognition correlate with decision effectiveness, particularly when comparing experienced operators to novices. It may also be pertinent to reassess previous studies using tools such as cognitive task analysis to examine whether skills and strategies that are prioritized by experts are from particular information modalities (e.g. Klein, 1997; McAndrew & Gore, 2013). Operators in different domains should also be examined, to assess if cognitive adaptions differ depending on operational context. It should also be noted that behavioural and neuropsychological dissociations do not necessarily imply the stochastic independence of their underlying processes or mechanisms. It is likely that all executive and sub-component tasks are jointly determined by some domain generality and some domain specificity (Jacoby, 1991; Morgan & Lilienfield, 2000). No task can be a pure measure of any particular function.

**Conclusions**

The current work provides insight into the cognitive state of AFOs at the time that appropriate tactical decisions were made, facilitating interpretation of methods typically used in NDM research to examine naturalistic decision making processes (Ask, & Granhag, 2007; Macquet & Skalej, 2015; Suddendorf & Henry, 2013). NDM research has also been criticised for lacking formalisation of constructs and clearly defined measurable parameters (Thomson et al., 2015). The use of standardised cognitive measures has provided quantifiable insight into the modality specific cognitive adaptions that occur when operating in naturalistic environments. As the field of NDM strives to improve the credibility and transferability of many methods (McAndrew, & Gore 2013). The current work has demonstrated how traditional cognitive tools can be used in highly immersive environments to provide ecological validity and reliability. It is important to emphasise that such techniques should be viewed as supplementary to, rather than oppositional to commonly used NDM methods.

**Author contributions**

Dr Aaron P J Roberts conducted the studies as part of his PhD thesis. He ran the experimental studies, analysed the data and co-authored the manuscript. Professor Jon Cole was the primary supervisor of the PhD. He guided the research directions, supervised the analysis and co-authored the manuscript.

**Acknowledgements**

The authors would like to thank Merseyside Police for their help and support in completing this work. In particular the expert guidance provided by Barkers and Stanno.

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