

**THE EFFECT OF LIGHT LEVELS AND TURBIDITY ON HUMAN FINE  
MOTOR PERFORMANCE AND VISUAL ACUITY UNDERWATER**

**BY**

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**THESIS**

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## **Abstract**

This thesis studied the effects of light levels and turbidity on human fine motor performance and visual acuity performance underwater with 18 participants (n=18), with varying levels of underwater experience. A fine motor task and visual acuity test were compared across three light levels and three turbidity conditions, simulating commercial diving conditions at various depths and different working areas underwater. The main findings of this study were that visual acuity decreased as turbidity levels increased ( $p=0.000003^*$ ). Increasing light levels will increase visual acuity regardless of the water turbidity level ( $p=0.007599$ ). Fine motor performance times increased despite the increase in turbidity ( $p=0.001336^*$ ) and light ( $p=0.000936^*$ ). This shows that learning and task experience will improve fine motor task performance. This improved performance may also be attributed to a reduction of peripheral stimuli when water turbidity increases, allowing the diver to focus on the task central to their vision. Interestingly, there was no interactional effect between the light levels and water turbidity for either the fine motor task or the visual acuity task. This shows that in the presence of water turbidity, increasing light levels will improve a diver's ability to perform fine motor tasks. There was no difference in Heart Rate Variability (HRV) between the turbidity conditions or the light levels for either task. HRV is an indicator of psychophysiological responses to stressful conditions. The lack of HRV response while submerged in the different water conditions can be attributed to the mammalian dive reflex, which reduces parasympathetic stress responses in humans and regulates heart rate (HR). The regulation of HR can reduce panic and create a state of calm when in stressful situations allowing a person to function adequately during a stressful or unnatural situation. Further studies that investigate the effects of light and turbidity underwater and the HRV response to these conditions are recommended to understand how humans can improve both performance and safety underwater, with implications for both commercial diver training protocols and operations.

### **Key words:**

**SCUBA, Submersion, Light, Turbidity, Fine Motor Performance, Visual Acuity, Heart Rate, Heart Rate Variability.**

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# **Chapter 1 Introduction**

## **1.1 Background to the study**

The underwater environment has always been fascinating to mankind and has lured explorers for many generations. Innovations in science have allowed humans to explore this inhospitable place for recreation and most importantly security or commercial gain (Levett & Millar, 2008). The underwater environment is harsh and ill-suited for humans. While operating underwater many environmental factors make this work potentially dangerous (Baddeley, 2000). These factors include but are not limited to depth, pressure, equipment, light, visibility, temperature, and strain on human operators (Egstrom et al., 1972).

Humans cannot breathe in water; in shallow dive depths, humans can utilise apnoea (temporary suspension of breathing), but in instances of greater depths or dive time requirements, breathing gear is needed (Maberry, 2000). For most commercial diving operations, apnoea is unsustainable on a large scale as most of the world's commercial diving happens either at greater depths than apnoea can allow or on a time scale that makes apnoea unfeasible (Pendergast & Lundgren, 2009a). Commercial diving operations can vary anywhere from a few meters to hundreds of meters below the surface (Bartholomew, 1979). With an increased depth of operations, more risks are associated with diving (Levett & Millar, 2008; Noh et al., 2018). Diving at depth exposes the operator to atmospheric pressure changes, increasing the amount of breathable gas consumed and saturated in their tissues. Operating at depth increases the amount of physical strain on a diver, requiring more effort to perform tasks. As depth increases, the level of light from the surface is reduced, reducing temperatures and visibility (Egstrom et al., 1972). The reduction in temperature requires operators to use exposure protection suits in either a wet or dry suit or, in some cases, a hot water suit for extremely cold temperatures (Baddeley et al., 1975; Bartholomew, 1979). Reducing light levels requires operators to use artificial light sources, such as a dive light attached to a dive helmet or a limb or by means of a remotely operated vehicle (ROV). The change in temperature and light levels can place mental strain on the dive operator, which can impair their cognitive functions, reducing their task performance (Baddeley et al., 1975; Lundell et al., 2020; Mäkinen et al., 2006). Underwater operations can stir up sediment from the dive site, resulting

in an increase in turbidity. Turbidity presence in water can further decrease temperature over time if there are large amounts of sediment clouds in the water blocking sunlight (Marshall, 2017). More commonly, turbidity will affect the visual acuity of a diver (Luria & Kinney, 1970). To compensate for this lack of visibility, a diver will need to use artificial light to perform their task; however, this may produce a glare effect due to the particles in the water being refracted and reflected back into the diver's vision (Barnard, 1961). This glare may have negative effects on task performance.

## **1.2 Research Question**

### **1.2.1 Statement of the problem**

Commercial diving operations occur in various bodies of water, from shallow bright pools to deep and dark ocean floors. While operating underwater, a diver might be exposed to varying levels of light and varying levels of sediment presence, resulting in changes in turbidity. Low light levels and turbidity in water may require the use of artificial light to allow the operator to perform a task adequately. However, there may be an impact on task performance in increasingly turbid environments. A dive operator may use a light source to see their task, but this light can be refracted and cause a glare to be reflected into their field of view (Luria & Kinney, 1970). This reflection can distract the operator and reduce task performance. There have been several studies conducted into human performance underwater (Dietmaier & Anegg, 2002; Elliot et al., 2011; Hancock & Milner, 1982, 1986), however, there is very little understanding of how light levels and turbidity can affect human performance underwater and if there is an interaction between light and turbidity on human fine motor performance and visual acuity while operating underwater. Fine motor performance is impacted by the underwater environment by increased pressure and reduced haptic feedback (Baddeley, 1966; Steinberg et al., 2015), while this feedback is not completely removed a diver may need to compensate for this with visual feedback. While fine motor functions (Hancock & Milner, 1982), and visual acuity (Luria & Kinney, 1970), are important for task performance underwater these factors need to be studied separately.

This leads to the question of identifying and understanding the relationship between light levels and turbidity underwater and if their effects have an interaction with both fine motor performance and visual acuity in human operators.

### **1.2.2 Aims and Objectives**

The aims of this study are to investigate and compare the effects of low light and reduced visibility on human task performance while operating underwater.

As follows, the objectives of the study were:

- 1) To quantify the effects of different light levels on human task performance underwater.
- 2) To quantify the effects of water turbidity on human task performance underwater.
- 3) To test and investigate whether there is an interactional effect between light levels and water turbidity on human task performance.

## **Chapter 2      Review of Literature**

### **2.1    Introduction**

Diving requirements involve gross motor function for body posture maintenance within a microgravity environment (underwater) (Lundell et al., 2020) and fine motor functions for assembly and precise actions such as welding and pipeline assemblies (Maberry, 2000). Fine motor functioning requires learned skills and situational awareness to successfully complete a task where the operator and the task interact with one another (Beling et al., 1998). Underwater environments are complex and can impact how humans function within them while performing tasks, and these kinds of adverse environments act on both the task and the operator (Gooden, 1994). For an operator to successfully complete a task, they must perform precise actions using fine motor functioning while maintaining or adjusting body posture based on the environmental factors that are acting on them at the time (Dalecki & Bock, 2014; Dalecki, et al., 2013; Geng et al., 2017). This will form the basis of this section, with the interactions between the working environment and operator(s), as well as the tasks being performed while underwater being described and explained in the sections that follow.

### **2.2    Environment**

The environment is any space in which work/ tasks take place. Within the context of this paper the working environment is any area where work is performed while submerged under a body of water. This section will expand on the most important aspects of an environment in which underwater work is conducted (2.2.1), how the environment changes with depth (2.2.2), how light levels change with changes in environment (2.2.3), the effects of turbidity on the underwater environment (2.2.4) and lastly the environmental dangers underwater (2.2.5).

#### **2.2.1    Underwater working environment**

The underwater working environment that operators are subjected to changes depending on their task (Pendergast & Lundgren, 2009), operators working on oil platforms can work in and around pipelines in the open ocean with overhead obstructions (Brady, 1976). Operators working on underwater oil pipelines can also work on the ocean floor in visibly poor conditions repairing pipes below them (Watt,

1985). The environment poses many threats and adverse conditions to underwater operators as there is a safety risk and performance deficits that they have to contend with. Operators can be in waters with predators that may influence their decision-making capabilities (Dalecki, et al., 2013; Hancock & Vasmatzidis, 2003).

Operators are expected to be experienced underwater and have a minimum of a year's diving experience commercially before being allowed to operate offshore (Watt, 1985). This may differ between certain countries regulations on commercial diving practices as well as instances of unrecognised commercial diving activities like illegal poaching of species or minerals. Divers are expected to be able to adapt approaches based on their environmental conditions, changing gear depending on both working depth and temperature (Dalecki & Bock, 2014a). The working environment of underwater operators is not optimal for fine motor performance with a deficit in feedback capabilities that the water imposes on the operator (Dalecki, et al., 2013a). There is a negative pressure gradient within the tissues of underwater operators when working at depths and this affects proprioceptor feedback at the distal region of limbs affecting both hand and foot functioning (Dalecki et al., 2012), making both fine motor assembly tasks more difficult and adjusting to the environment more difficult.

### 2.2.2 Depth

Depth of working environment places more strain on operators as the deeper they descend below sea level the more pressure they are exposed to (Gooden, 1994; Noh et al., 2018). When working at pressure there is a risk of increased air consumption due to air particles being forced closer together so each breath that is taken takes more air consequentially, as well as more air is needed to fill the lungs to their 'normal' capacity (Castagna et al., 2018). Breathing gas underwater at pressure has changes to the human dive response (Gooden, 1994; Lundell et al., 2020). At depths oxygen becomes increasingly toxic and poses health risks to the operator so there is a need to mix gases in order for the diver to complete a task.

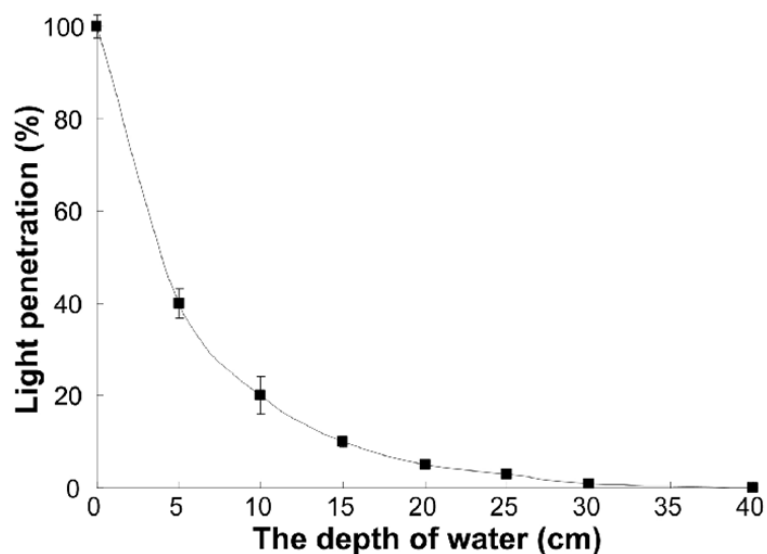
Oxygen toxicity is a real threat to both performance and cognition underwater and can make simple tasks incredibly difficult (Thom et al., 2012a). Divers also consume inert gases when using SCUBA apparatus taking up nitrogen which forms minute bubbles in their tissues (Thom et al., 2012a). These bubbles are then diffused throughout the

body and must be exhaled safely before return to the surface. Nitrogen bubbles are minuscule but as the diver ascends the pressure gets lower so gas begins to expand, this causes the nitrogen bubbles to move around the bloodstream of a diver and eventually can get trapped within joints resulting in sharp pains at the joint site (Lundell et al., 2020; Thom et al., 2012a). In extreme cases these bubbles can form around the spinal column forcing a diver to hurl (bend) over, or in other soft tissues and joints around the body causing discomfort and pain, this is known as *decompression sickness* (DCS) (Thom et al., 2012a).

Depth not only affects how gas is breathed and absorbed by the body but also how much is visible, with the increase in depth comes a decrease in visible light from the sun. This means that all colours except blue are filtered out when the diver descends below 20 metres. This can affect how operators see their environment and reduce their visual feedback from the system, in turn reducing their performance capabilities (Dalecki, Bock, et al., 2013a; Noh et al., 2018; Pendergast & Lundgren, 2009). Depth also affects the temperature that operators are exposed to.

### 2.2.3 Light

Light levels are important to dive operators for several reasons, mainly being safety and situational awareness, as well as communication. Light levels allow divers to maintain situational awareness and orientation towards their task (Marshall, 2017). Working at varying depths will have an impact on light levels (Potts et al., 1987). As divers operate at deeper depths there is less natural light from the surface as water absorbs light (Kim et al., 2018), (figure 2.1). The deeper a diver operates the darker



their environment will become requiring some form of artificial light either by a dive light or external light source provided by an ROV.

Another consequence of depth is a shift in colour due to waters' light absorption properties. Light wavelengths change with depth as colours are absorbed (figure 2.2, taken from NOAA). Red light waves are absorbed first, then yellow light waves. Blue light waves can travel the furthest through water (Marshall, 2017). The change in light waves as depth increases, can obscure or even render some instruments or critical safety information on dive gear unobservable based on the colour of the ink used. This can pose a risk to the dive operator if critical information is easily overlooked due to the colour shift. In instances where gear or safety information is difficult to see artificial light is crucial.

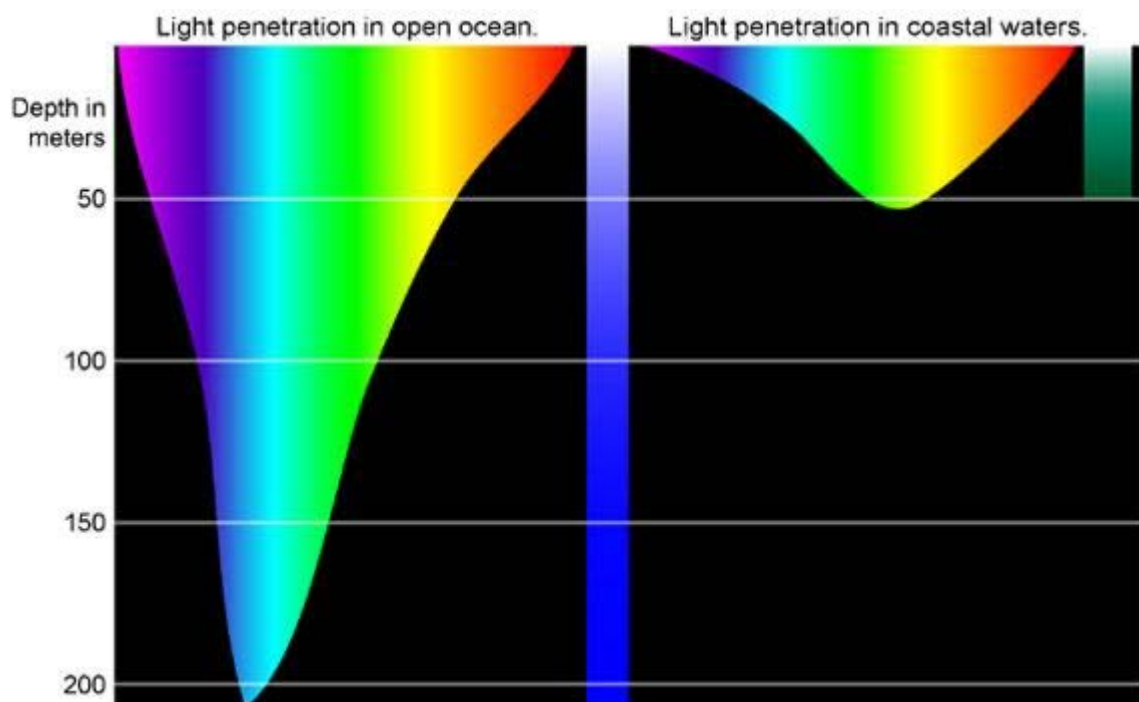


Figure 2.2 Colour filtration through water as depth increases

Light not only plays a role in observing the environment and dive gear but also crucially in communication with fellow divers as in many cases dive signals or sign language can be the only form of communication between divers. If there is inadequate light,

there is a chance that communication between divers will be negatively affected. This can pose a risk to safety as well as the diver's tasks when working in a group.

Lower light levels can be more cognitively taxing on a diver requiring more concentration than diving in the presence of brighter lights. With divers having to either concentrate or strain more to focus on what they are meant to be observing or working on (Potts et al., 1987). Diving where there is little, or no light can increase the risk of mistakes or miscommunication with fellow divers as hand signals could be overlooked or missed entirely (Endsley, 2015; Merchant, 2011). This can lead to serious injury or be potentially fatal (Elliott, 2003).

#### 2.2.4 Turbidity

Turbidity is the presence of suspended particles in water, which can be made up of living particles, i.e. Algae or microscopic organisms, or these particles can be made up of inorganic materials such as debris or sediment from degraded structures or the ocean floor/ riverbed (Milam, 2010). These particles refract and absorb light, reducing visibility underwater making simple tasks more difficult or more cognitively taxing (Milam, 2010). Increased turbidity in water can lead to a reduction in situational awareness and disorientation (Milam, 2010). In extreme cases turbidity can reduce or eliminate vision completely (He & Nan, 2012).

The presence of turbidity in water adds the risk of communication issues between divers, with divers relying on hand signals or sign language to communicate, particularly within the recreational spaces and less mainstream organised commercial diving operations, where operators do not have access to underwater radio communications. With an increase in turbidity there is a higher chance of communication being overlooked reducing the safety of a dive operation (Dalecki et al., 2013; Milam, 2010). This is made increasingly worse as divers move further away from each other as turbidity decreases visual distance.

In some extreme cases of hazard diving, divers submerged in sewage or oil pipelines operate in viscous liquid. This viscous liquid is made up of a large amount of large suspended particles of oil, sewerage etc. The turbidity can increase physical demands in order to manoeuvre in this thicker liquid as well as cognitive demands where divers will likely be diving in a liquid that does not allow light to pass through the diver must

rely solely on haptic feedback commonly through gloves where visual feedback is not viable or absent altogether (Dalecki et al., 2013; Kinney et al., 1970; Marshall, 2017).

When diving in turbid water and visual acuity is affected a dive operator may use artificial light in order to complete a task or navigate, however there may be a risk that too much light is not a good thing as the more artificial light introduced to the environment may be reflected back into the operators eyes in turn further reducing their visual field and making the task even more difficult (Milam, 2010). There are other methods that can assist a diver operate optimally underwater, but this introduction of additional gear can increase the task demands on the diver which can impact performance (Bartholomew, 1979; Pendergast & Lundgren, 2009b).

Turbidity presence in water can also have adverse effects on water temperature as suspended particles in the water reduce the amount of warmth transmitted through sunlight into water thus in instances of high turbidity water temperatures can decrease (Davies-Colley & Smith, 2001; He & Nan, 2012).

#### 2.2.5 Temperature

Temperature has a unique role in how humans' function, both on land and underwater, as human physiological processes have ranges of temperatures in which they function optimally (Cheung et al., 2003; Cui et al., 2013).

When the temperature is high, the human physiological response is to produce sweat in order to cool down the body and maintain optimal temperature for functionality (Liu et al., 2017). When diving however, often, in offshore commercial operations, the diver is exposed to prolonged periods of cold water, which affects how they operate (Tipton et al., 2013). When working in cold temperatures, there is a need to maintain optimal body temperature, which means that dive operators' basal metabolic rate increases to warm them up (Lundell et al., 2020). Consequently, divers operating in extreme cold conditions wear warm water suits, with warm water fed into their suits by their umbilical to keep them safe and operating (Lundell et al., 2020; Pendergast & Lundgren, 2009).

When it comes down to the actual operation of commercial divers, they are required to manipulate their environment to complete their tasks. This can be made difficult when in cold temperatures as studies have shown that there is a reduction in cognitive

ability, which reduces feedback capabilities from the visuo-spatial system (Dalecki, et al., 2013). There are also reduced parasympathetic and sympathetic nervous system responses when diving in colder waters (Dalecki & Bock, 2014a). These factors contribute to a reduction in task feedback making task performance durations longer and more difficult (Cui, et al., 2013; Mäkinen et al., 2006b).

As temperatures reach adverse conditions there is a risk that both performance and situational awareness decreases which can not only affect task performance and completion but also how the operator perceives their environment and how they interact with their equipment. Colder water however has been shown to reduce HR response and reduce HRV of the dive operator (Elliot et al., 2011; Lundell et al., 2020; Noh et al., 2018).

#### 2.2.5 Environmental Dangers

Working underwater has its fair share of dangers, there is no way to breath without assistance, there are adverse temperatures and little visibility with the presence of underwater predators. With the presence of predators inexperienced divers may become uncomfortable and may not be able to perform as well, as they are devoting their situational awareness and attention resources to this new perceived threat as opposed to the task at hand (Elliot et al., 2011). Dangers also include the need to monitor equipment and air consumption (Gooden, 1994; Levett & Millar, 2008), while some of this is aided by a surface crew when operating commercially, the operator still needs to be aware of their equipment, the task and their surroundings which takes up a large amount of their attention resources (Dalecki et al., 2012; Hancock & Vasmatzidis, 2003; K. Liu et al., 2013). Depth is also one of the most dangerous factors that operators are exposed to, with the increase in depth comes more risk of decompression sickness and oxygen toxicity so there is a need to mix gases that the operator breathes with increased safety stop times (Levett & Millar, 2008). These dangers pose both a risk to task performance but most importantly towards operator safety.

## 2.3 Underwater Operator(s)

The operator is any diver who is working in an underwater environment and tasked with completing a specific goal. This section will expand on the operator's function(s) underwater and the effects that submersion has on their task functioning. The most important aspects of a human operator underwater are the human diving response (2.3.1), assisted breathing (2.3.2), attention and vigilance (2.3.3), human vision (2.3.4), manual dexterity (2.3.5) and most importantly safety (2.3.6) These aspects of underwater work are discussed below.

### 2.3.1 Human Dive Response

The human diving response, also known as the 'mammalian dive reflex' is a parasympathetic response to submersion and begins as soon as an operator descends below the water surface (Gooden, 1994; Schipke et al., 2001a). The activation of the parasympathetic nervous system is a control mechanism to regulate bodily functions in a pressurised and adverse environment (Gooden, 1994). When submerged the human heart rate reduced thought of as a means to conserve oxygen, however there is an increase in *heart rate variability* (HRV) indicating the presence of adverse conditions or discomfort (Lundell et al., 2020; Schipke et al., 2001a, 2001b). While HR is reduced the variation of inter-beat cycles is increasingly stable as depth increases (Dalecki & Bock, 2014; Schipke et al., 2001; Dalecki et al., 2012; Noh et al., 2018). The Musculo-skeletal system is also affected by submersion as there is a reduction in gravity, so the muscles in limbs are not as contracted and there is less joint compression to keep the operator upright (Dalecki & Bock, 2014), so there is a possibility to move around in a fully three-dimensional space (Lundell et al., 2020; Schipke et al., 2001). With this comes limitations, as the operator needs to maintain body posture for task completion which means that they must place effort and resources into the maintenance of body posture limiting their ability to function and perform precise actions (Dalecki, et al., 2013; Dalecki & Bock, 2014). With the constantly changing environmental conditions by way of current and surge the operators constantly need to be aware of their environmental space and how it is changing.

### 2.3.2 Assisted Breathing

Humans cannot breathe underwater and need some form of assisted breathing. This can be by means of a snorkel, compressed gas cylinder and regulator or dive helmet and umbilical cord (Watt, 1985). When at depths the air operator's breath can become toxic and hazardous to their health (Watt, 1985). Breathing compressed gas has been shown to affect the heart rate response in divers, showing an increase in heart rate when breathing a Nitrox mix, and a reduced heart rate response when breathing normal air (Lundell et al., 2020; Schipke et al., 2001). Nitrox is a mixture of oxygen and nitrogen gas in a SCUBA cylinder than can vary in concentrations, for example Nitrox32 is 32% oxygen and 68% Nitrogen (Mitchell & Doolette, 2017).

This is possibly as a regulatory mechanism to air being forced into their lungs by the compressed gas cylinder (Castagna et al., 2018). As humans need to have some form of assisted breathing while working for prolonged periods of time underwater it is vital that the assisted breathing modality does not affect how they function while performing a task (Dalecki, et al., 2013a; Schipke et al., 2001). The most common form of assisted breathing is SCUBA (self-contained underwater breathing apparatus) and is used recreationally as well as commercially (Green & Powell, 1988; Watt, 1985). SCUBA is not compatible with prolonged diving periods so there needs to be another means of supplying divers with air. When diving for prolonged periods of time the dive operator would have a surface support crew supplying them with compressed gas fed to the operator from the surface on a boat, platform or jetty (Watt, 1985).

Surface support and dive operating crews will use an umbilical cord to supply the diver with air. This umbilical is used for both surface fed air supplies to equipment and dive habitats and operators working on saturation dives (Watt, 1985). Saturation dives are when the operators live and work at pressure. Saturation divers are in their working environment for days or weeks at a time performing welding or assembly tasks within a habitat moving between their living and working habitat by means of a dive bell (Watt, 1985). Living for weeks at a time at pressure means that when divers ascend, they must do so incredibly slowly to avoid health risks associated with decompression sickness (Levett & Millar, 2008).

Divers using assisted regulator breathing modalities can have drop off in performance as there are bubbles exhaled and more noise produced by their breathing apparatus,

this can add distractions to their environment and provide increased stimuli that directs diver's attention resources away from a desired task (Geng et al., 2017; Hancock & Vasmatazidis, 2003), effecting their cognitive functioning and visual capability and as a consequence reduce their ability for fine motor functioning and task completion (Hancock & Vasmatazidis, 2003).

### 2.3.3 Attention and Vigilance

Commercial diving poses a distinct set of difficulties that require increased focus and awareness compared to working on land. Divers work in intricate and frequently dangerous underwater conditions, where staying focused is essential for task performance and safety. Developing efficient training and operational procedures requires an understanding of the elements that affect attentiveness and vigilance in these situations. Commercial diving involves many tasks to complete a job and remain safe, these tasks can accumulate in what is referred to as task loading.

Task loading might comprise activities like as equipment monitoring, navigation, communication, and the execution of specialized labour tasks like welding or inspection. A reasonable workload enables divers to work efficiently and have time for unanticipated events. Overloading a diver with tasks, however, might overwhelm them and increase the likelihood that they will overlook important safety precautions or perform worse. This is especially problematic when scuba diving because the task load becomes more complex due to the limited breathing gas supply and possible decompression obligations (Maberry, 2000; Mitchell & Doolette, 2017). Stressful underwater environments and conditions can cause perceptual narrowing. This is a condition in which a person's attention becomes narrowed and their capacity to interpret peripheral information is reduced. Weltman and Egstrom (1966), looked at this effect to study how quickly inexperienced divers responded to peripheral visual cues while doing central tasks. They discovered that when diving, some divers showed noticeably longer reaction times to peripheral inputs, which may indicate that stress is a factor in a reduced perceptual field (Weltman & Egstrom, 1966).

A diver's situational awareness may be compromised by this narrowing, making it more difficult to recognize and react to unforeseen environmental events. Nitrogen narcosis, which affects the central nervous system and impairs cognitive abilities, can

be brought on by breathing compressed air at elevated ambient pressure. Executive skills, including working memory, cognitive flexibility, and inhibitory control, are selectively compromised at a depth of 20 meters (Steinberg & Doppelmayr, 2017). This increases the likelihood of accidents during complex activities by impairing a diver's capacity to make prompt and accurate decisions, adjust to changing circumstances, and suppress inappropriate responses.

For commercial diving operations to be conducted safely and effectively, attention and vigilance are essential (Bartholomew, 1979; Maberry, 2000). Diving professionals can improve operational safety and efficiency by comprehending the environmental factors that affect these cognitive functions and putting procedures in place to regulate task loading and reduce cognitive limitations. These environmental factors and conditions and how they impact human performance need to be understood in order to improve attention and vigilance underwater.

#### 2.3.4 Vision

Dive operator's main way of understanding their environment and tasks is to observe, meaning that they need to be able to look at problems on rigs, ships etc. in order to make an informed decision on their task (Dalecki & Bock, 2014; Steinberg et al., 2015). Vision changes underwater as there is a light gradient that changes when submerged, there is less red and green light rays below 20m of water meaning that the majority of things that are observed underwater are graded in a blue hue (Merchant, 2011). This can be combatted with the use of a diving light that is attached to a dive helmet or held in the hand of an operator. But vision is not the same underwater as it is on land. Humans use two eyes to determine spatial awareness and depth perception, however underwater there are factors that interfere with the visual response of operators (Dalecki, et al., 2013; Dalecki & Bock, 2014).

##### 2.3.4.1 Vision Underwater

Vision underwater is magnified and warped based on the reflection and refraction of light moving through water particles (Ann et al., 1969). Some diving gear such as masks or helmets can have magnification-adjusted screens so that operators view their environment in a 1:1 meaning that it is the same visuo-spatial response that they

would receive on land (Ann et al., 1969). Vision underwater affects how the operator interacts with their task (Dalecki & Bock, 2014b). With regards to fine motor performance, the operator needs visual feedback to determine if they are progressing correctly with their task, and if there is a magnification effect then this can be difficult to assess correctly (Steinberg et al., 2015). When underwater due to the magnification effect from water objects can appear stretched or warped (Ann et al., 1969), which can make assembly, observation, or welding tasks difficult (Dalecki, et al., 2013a; Dalecki & Bock, 2014). Studies have shown that when performing tasks underwater (Steinberg et al., 2015), experience plays a vital role. With the magnification effects on vision underwater an experienced diver can adjust their movement to compensate for the magnification effect (Dalecki & Bock, 2014; Steinberg et al., 2015), meaning that instead of reaching for an object in front of them the operator can see, the more experienced diver will in turn track their hand towards to object until contact is made. This in turn will reduce performance times for all operators underwater, however, the drop off in performance times is mitigated by levels of dive experience (Dalecki, et al., 2013a).

#### *2.3.4.2 Visual Feedback*

Visual feedback is the process by which people are given visible information about their environment and tasks, allowing them to modify and improve their actions accordingly (Sigrist et al., 2013). This is essential to working underwater. For example, visual feedback allows a dive operator to watch their actions and environmental conditions and adjust as needed to enhance performance (Baddeley, 2000; Sigrist et al., 2013).

Visual feedback is essential in commercial diving for carrying out difficult tasks, guaranteeing safety, and preserving spatial orientation in the demanding underwater environment (Merchant, 2011). Effective visual feedback mechanisms are essential for divers due to the special conditions that exist underwater, including decreased visibility, changed light refraction, and the need for accurate manual tasks. Visual feedback is especially crucial for jobs that call for fine motor abilities, like biological sampling, underwater welding, and equipment inspection (Huang & Hwang, 2012; Merchant, 2011). Divers can improve task accuracy and efficiency by quickly correcting mistakes when they can view and evaluate their motions. For example,

visual feedback aids in maintaining proper alignment and speed during underwater welding, both of which are essential for the integrity of the weld.

Several challenges stand in the way of efficient visual feedback in the underwater environment. Visibility can be greatly diminished by elements including turbidity, low light levels, and light absorption and scattering. Divers had a 30% recall error rate for subsea marker panels, according to Leach and Morris (1993), underscoring the effect of poor visibility on task performance. The apparent size and distance of objects, as well as depth judgment, can be distorted by the refractive qualities of water (Leach & Morris, 1993). If a diver has difficulty seeing underwater and their visual feedback is limited there is a chance that their fine motor performance will decrease, in turn making their task more difficult as well as reducing their safety (Dalecki & Bock, 2014; Renner & Beversdorf, 2010).

### 2.3.5 Manual Dexterity

Manual dexterity is the coordinated movements of the hand and fingers for task performance. Manual dexterity is used to manipulate tools or equipment to complete a task effectively (Cheung et al., 2003). When diving manual dexterity is important for a number of reasons, the handling of equipment or tools, communication with fellow divers, and interacting with the environment or task. Manual dexterity is vital for diving but can be affected by depth and or pressure, visibility, and certain physiological factors like nitrogen uptake in the body (Baddeley, 1966), and psychosocial factors like anxiety (Kneller et al., 2012).

#### 2.3.5.1 *Fine Motor Performance*

Motor function or motor skills are voluntary movements of the body enacted by the contraction of skeletal muscles. Skeletal muscles are stimulated by nerve impulses that flow through neurons within a motor unit. Motor Units are made up of a single motor neuron that innervates muscle fibres, the axon splits into multiple strands so that many muscle fibres can possess a motor end plate (Seidler et al., 2004). Motor units are normally confined to a small single muscle tissue area and depending on the movements generated by the muscle there can be anywhere between 100 to 2000 muscle fibres attached to a motor unit (Seidler et al., 2004). Muscles responsible for

smaller and more precise movements will contain fewer muscle fibres attached to motor units, whereas powerful or gross muscular movements are performed by motor units innervating large amounts of muscle fibres. Muscular actions are performed by stimulated muscle fibres within larger muscle tissues, these movements are produced by tension developed within "*twitch-type cells*" (Eberstein & Goodgold, 1968).

Motor functioning takes two forms. Gross motor functioning, produced by larger muscle groups for greater and more powerful actions performed by the body (Beling et al., 1998), an operator would require gross motor control for the maintenance of body posture underwater, and fine motor functioning produced by smaller muscle groups for precise actions (Bright & Asada, 2017). An underwater operator would require fine motor recruitment when performing precise tasks such as welding, adjusting equipment and manual assemblies of pipes (Watt, 1985). Fine motor functioning is a precise movement of smaller skeletal muscles to perform smaller, more precise actions from the wrist/ hands, fingers, feet, and toes (Beling et al., 1998). Fine motor skills can become impaired over prolonged periods of time due to both cognitive and muscular fatigue (Dalecki et al., 2012). Discrete tasks will naturally require more fine motor functioning and will utilise smaller skeletal muscles in order to perform a task (Beling et al., 1998; Hancock & Vasmatazidis, 2003).

When there is a period of inactivity or a period of non-use there is a drop off in fine motor function performance, however this can be contested by motor learning (Beling et al., 1998; Seidler et al., 2004). Motor learning is the stimulation of development of motor neurons within muscle tissue in order to perform actions repeatedly. Motor learning is a learned stimulus response and the development of motor skills through learning and repetition. This is regarded as a permanent skill that is learned and retained (Fitts, 1967). There are generally three stages to motor learning discussed by Fitts (1967), 1.) *The cognitive phase*, 2.) *The associative phase*, and 3.) *The autonomous phase*.

The cognitive phase involves the operator learning how to use the tools and equipment that are available to you, actively thinking about how to position your body to use the tools and equipment and ultimately thinking about the outcomes from using said equipment and tools (Kee, 2019). The associative phase is where the operator

performs their task with any given piece of equipment or tool with from their knowledge about the tools/ equipment and the task using information from their environment to either aid or inform them of their task (Kee, 2019). Progressing from this stage to autonomy can take any period of time depending on the task complexity that is to be learned and performed. The Autonomous stage is where the task being performed by an operator seems to be effortless and requires less concentration than novel tasks, along with negative aspects of the task, either through uncomfortable environments or difficult conditions, having less impact on the operator due to their familiarity with the task at hand, allowing for greater awareness towards the task (Kee, 2019). There may however be a drop off in performance after a period of inactivity (Beling et al., 1998), but performance can improve once an operator returns to said activity and refamiliarizes themselves with the task once more.

Fine motor function is limited by injury, illness, cognitive disabilities, physical disabilities, or environment (Garber et al., 2011; Seidler et al., 2004). When performing fine motor functioning tasks (Seidler et al., 2004), feedback from the task is important, ensuring that the underwater operator can adjust their input controls to continue performing the desired task.

Studies on fine motor functioning and precision performance underwater has shown that there is a drop off in performance underwater compared to on land performance (Dalecki, Dern, et al., 2013; Mäkinen et al., 2006a; Schipke et al., 2001a), possibly as a result of partial pressures and reduced blood flow to limbs, but this can also be attributed to increased stimuli underwater and a changing environment. Increasing stimuli exposure has shown to reduce performance (Dalecki et al., 2012; Steinberg et al., 2015), both cognitively and on fine motor performance by increasing the demands on the attention resource system.

#### *2.3.5.2 Tactile Feedback*

Tactile feedback, proprioception and touch is altered when submerged due to the properties of the water, or through the need to use protective equipment like gloves and or wetsuits. When diving in water there is hydrostatic pressure which is felt on the skin (Brady, 1979). This compressive feeling can reduce sensitivity to tactile feedback when manipulating gear or tools to perform a task underwater. Hydrostatic pressure

combined with breathing compressed gas results in increased pressure in joints which can reduce the mobility of the arms or legs as well as their extremities which can add to the difficulty of manipulating equipment or tools where discrete movements are required (Castagna et al., 2018; Pendergast & Lundgren, 2009a).

### 2.3.6 Safety

Safety is the number one task for any dive, be it recreational or commercial (Elliott, 2003). Safety practices are thoroughly engrained in divers throughout their training. Experienced divers are always safe divers as they have the necessary skills and adaptability for most situations they may encounter. For divers to be safe when operating underwater they need to understand their environment and their limits when on a dive (Bennet & Mcleod, 1984). With the dangers of the underwater environment being ever present when diving for a commercial operation there is a certain level of experience that is required due to the dangerous nature of the work, either from extremely harsh environments where one mistake can be fatal to working on sites that require high levels of expertise and situational awareness (Bitterman et al., 2009; Stanton et al., 2001). If a diver is not adequately qualified, they can pose a risk to the whole group. This is why for commercial diving operations experience is a key requirement (Bartholomew, 1979).

Experienced divers may not require the same amount of cognitive processing as inexperienced divers as their diving tasks become automated and second nature due to learning (Godden & Baddeley, 1975). This can allow them to focus on multiple tasks with minimal drop off in performance. Experienced divers are also more likely to be aware of the risks of their task at hand so they can pay more attention to reduce to likelihood of negative consequences of diving or environmental factors that could jeopardise the safety of the dive (Kinney et al., 1970). In order to be safe underwater an operator needs the specific gear and tools required in order to complete their task and return to the surface safely (Kinney et al., 1970). As well as safe diving practices and close monitoring of dive tables to reduce the likelihood of contracting decompression sickness on their ascent (Levett & Millar, 2008). However, in some instances a rapid ascent is possible if the commercial diving company has access to a decompression chamber (Maberry, 2000). This allows the diver to return to the

surface and decompress in a dry environment and out of their wet dive gear (Maberry, 2000).

To improve on dive safety more needs to be understood on how the environment can affect a diver, both through environmental interactions through light levels and turbidity, and how the diver can adapt their equipment to meet the needs of the present environment that they're exposed to.

## **2.4 Task Requirements**

The task entails any form of work that takes place in the underwater environment to accomplish a goal. This section will explore the task requirements of divers underwater.

Operators are required to perform various tasks underwater which can entail research observations, mapping, manual assembly tasks, welding, search, and recovery etc (Green & Powell, 1988). while these tasks are complex in their own regard, they are made increasingly difficult when the work environment is taken into consideration (Dalecki et al., 2012; Dalecki & Bock, 2014). The underwater environment makes tasks increasingly difficult with the increase of factors to be considered. When diving underwater divers have to maintain situational and objective awareness (Dalecki et al., 2012), considering their depth and visibility levels (Noh et al., 2018), where their tools and gear is in relation to their position (Green & Powell, 1988), monitoring currents and surge and the effects these factors impose on the current task (Watt, 1985).

The more technical a dive is the more work needs to be done in order to complete a task successfully. When diving at increasing depths there is a need for mixing gas so that the operator remains as cognitive as possible without reducing safety (Powell & Harris, 1990). Simple shallow dives do not require a vast amount of equipment in order to sustain the operator's ability to successfully complete their task (Green & Powell, 1988), at shallow dives there is increased light intake and a reduction in gas consumption as a result of reduced pressure and more sunlight reaching shallow depths. This means that divers can perform tasks for longer at shallow depths and can even perform better at a given task than if they were at a deeper depth (Castagna et al., 2018; Thom et al., 2012b). At deeper depths there is less light from the sun that

reaches divers, so they often have to carry or mount lights so that their task is visible (Noh et al., 2018; Watt, 1985). When diving in deeper depths or in bodies of water that are darker due to a lack of light or increased murkiness there is more risks of losing bearings and getting lost (Green & Powell, 1988; Noh et al., 2018).

Deep dives pose risks to the divers air consumption as well. The deeper a diver is operating underwater the more air they naturally consume due to the inert pressure. The gas molecules are condensed more and more the deeper a diver goes, so every inhalation will draw in more air molecules than if the diver was at 1 atmosphere (sea level). (Thom et al., 2012a), this means that dives at depths are generally shorter unless the divers are living at depth in a dive habitat, living under the continuous pressure of said depth. These task requirements are reliant on the overall job at hand and can vary from day to day (Green & Powell, 1988). When saturation diving there is generally one task that needs to be completed over a longer period so dive operators will live at a given depth and work at the same depth, this is due to the safety of the diver from constant exposure to pressure (Levett & Millar, 2008). If the dive operators were to surface after being hundreds of meters below sea level their decompression time would negate the value of having human operators working at that depth and could not be completed in a day, this is why operators live and work at depth and surface incredibly slowly once their task is complete.

## **2.5 Importance of Understanding Underwater Work**

Underwater work is vital for many of the world's industries from internet provision, mineral and gas acquisitions to environmental sustainability (Watt, 1985). If there is work that is done underwater it is important to the daily lives of humans that may never even know it. In order for the work done underwater to be effective it needs to be safe and productive (Elliott, 2003). By understanding the working environment commercial divers operate in and the possible impacts that the environment has on their task performance it is possible to try and balance the environmental demands as well as the work demands that is placed on the operator. Balancing these demands can lead to increased safety and in turn can improve underwater productivity. One step in understanding these demands is to investigate how the underwater environment affects a dive operators' visual acuity in both clear water and varying levels of turbid

water, as well as how these water conditions can affect their fine motor skills which can be considered crucial for diving safety (Bitterman et al., 2009).

## **Chapter 3      Methodology**

The aim of this study was to investigate the effects of light levels and turbidity on human fine motor performance and visual acuity underwater and to identify any interactional effects between light levels and turbidity on human fine motor performance and visual acuity while underwater.

### **3.1    General Experimental Concept**

To investigate the effects of light levels and turbidity on human task performance underwater, participants were tested in three water and light conditions: clear water, low turbidity, and moderate turbidity. The testing sessions took place in a laboratory setting. Participants were tested under three lighting conditions (low, medium, and bright light) and three water turbidity conditions (clear water, low turbidity, and moderate turbidity). All the participants were tested under all nine conditions (repeated measures design). During the testing conditions, participants performed a fine motor task consisting of a shape sorting puzzle and a visual acuity task consisting of ten displays per light condition, totalling 30 displays per water turbidity condition.

### **3.2    Hypothesis**

The main hypothesis for this study was that fine motor performance and visual acuity would differ between light levels (low, medium and bright light) and water turbidity (clear water, low turbidity and moderate turbidity). The hypothesis was formulated in an undirected manner due to the lack of clear evidence that human performance decreases underwater.

- 1) Task performance would differ between water turbidity conditions: Clear water, Low turbidity and Moderate turbidity. Tasks include fine motor function and visual acuity measures.

Alternative hypothesis: There will be a difference in task performance between the water turbidity conditions

$$H_1: \mu P_C \neq \mu P_L \neq \mu P_M$$

Null hypothesis: There will be no difference in task performance between the water turbidity conditions

$$H_0: \mu P_C = \mu P_L = \mu P_M$$

Where:

P – Task performance

C – clear water

L – low turbidity

M – moderate turbidity

2) Task performance will differ between the three lighting conditions: Low, medium and bright light. Tasks include fine motor function and visual acuity measures.

Alternative hypothesis: There will be a difference in task performance between the light level conditions

$$H_1: \mu P_L \neq \mu P_M \neq \mu P_B$$

Null hypothesis: There will be no difference in task performance between the light level conditions

$$H_0: \mu P_L = \mu P_M = \mu P_B$$

Where:

P – Task performance

L – low light

M – medium light

B – bright light

- 3) Heart rate variability will be between the water turbidity conditions: Clear water, low turbidity and Moderate turbidity

Alternative hypothesis: There will be a difference in heart rate variability between the water turbidity conditions

$$H_1: \mu H_C \neq \mu H_L \neq \mu H_M$$

Null hypothesis: There will be no difference in heart rate variability between the water turbidity conditions

$$H_0: \mu H_C = \mu H_L = \mu H_M$$

Where:

H – heart rate variability

C – clear water

L – low turbidity

M – moderate turbidity

- 4) Heart rate variability would differ between the three lighting conditions: Low, medium and bright light.

Alternative hypothesis: There will be a difference in heart rate variability between the light level conditions

$$H_1: \mu H_L \neq \mu H_M \neq \mu H_B$$

Null hypothesis: There will be no difference in heart rate variability between the light level conditions

$$H_0: \mu H_L = \mu H_M = \mu H_B$$

Where:

H – heart rate variability

L – low light

M – medium light

B – bright light

- 5) There will be an interactional effect between light levels and water turbidity on task performance.

Alternate hypothesis: There will be an interactional effect between light levels and water turbidity on task performance.

Null hypothesis: There will be no interactional effect between light levels and water turbidity on task performance.

### 3.3 Conditions

The study consisted of four sessions, one habituation session (session one) and three water clarity testing conditions: Underwater in clear water, underwater in low water turbidity, and underwater in moderately turbid water. Water conditions were not permuted due to environmental factors such as drought and water restrictions in the area leading to the inability to refill the tank with clean water on a weekly basis. This is acknowledged as a limitation of the study.

The study also included three light level conditions (low, medium and bright light). Light levels were permuted for each of the water clarity testing sessions.

Table 3.1: Water and light conditions for testing sessions

	<b>Water Conditions</b>		
	<b>Clearwater</b>	<b>Low turbidity</b>	<b>Moderate turbidity</b>
Low light	Session 2	Session 3	Session 4
Medium-light	Session 2	Session 3	Session 4
Bright light	Session 2	Session 3	Session 4

### 3.4 Task

#### 3.4.1 Fine motor task

The task used to assess fine motor functioning was a shape-sorting puzzle. The shape puzzle was fixed to a table allowing the puzzle pieces to sit in the corresponding shape without falling out. If a piece was placed into an incorrect shape, the puzzle could not be completed. The table was set at a working height so that all participants could stand upright in front of it and complete the task without the need to bend over.



Figure 3.1 Shape puzzle board for the fine motor task.

#### 3.4.2 Visual Acuity Task

The task used to assess visual acuity underwater was a Landolt-C ring visual acuity test. The C rings were displayed from outside of the water tank by the researcher while the participant stood upright in the tank. The distance from where the Landolt-C rings were displayed behind the glass to the participant was 1.1 metres with each C-ring displayed having a radius of 8mm. Participants had to point in the direction of the opening of each ring displayed to them.

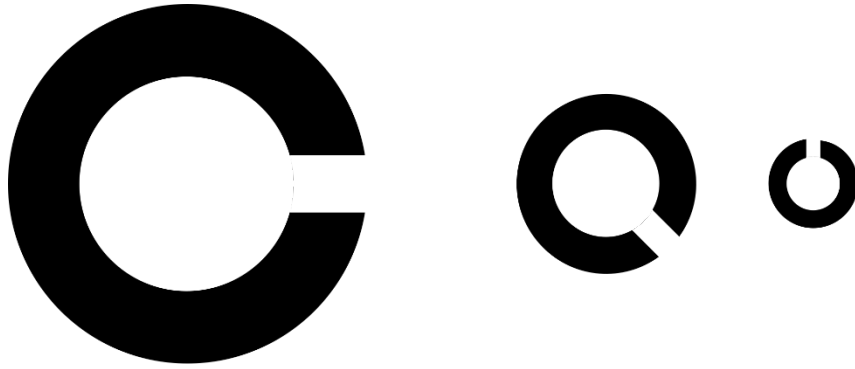


Figure 3.2 Landolt C rings in various sizes

### 3.5 Controlled Variables

#### 3.5.1 Depth

Depth was controlled to 2m below the water surface to mitigate the effects of pressure, light change and breathing requirements on cognitive and fine motor performance.

#### 3.5.2 Temperature

Temperature was controlled to 32 degrees Celsius (°C) to avoid the effects that cold has on cognitive and fine motor performance.

#### 3.5.3 Breathing modality

Participants used SCUBA equipment (cylinder and regulator) attached to a back plate while underwater so that they could complete the tasks with consistent breathing.

#### 3.5.4 Vision

Participants used a clear dive mask while performing the underwater tasks so that their vision would not be impaired drastically by the effects of submersion. The dive mask was made of clear silicone allowing a degree of peripheral situation awareness.

## **3.6 Ethical Considerations and Participants**

### **3.6.1 Ethical Considerations**

Ethical approval for the study was obtained from the Rhodes University Human Research Ethics Committee (RU-HREC). (*Ethics Approval Number: 2023-5747-7451*).

Ethical considerations for this study were to minimize the risk to the human participants. The testing tank was no deeper than 2m, this removes the risk of any decompression sickness or adverse pressure. This depth also allows for rapid ascension in the event of an emergency. There was a ladder in the tank to allow for easy entry and exit of the tank. Participants were monitored by the researcher at all times while in the water tank.

### **3.6.2 Participants**

Participants were selected from the wider Makhanda area as well as Rhodes University staff and students, preferably but not limited to people with diving and or underwater experience. Snowball recruitment was also utilised, and an email was sent to various departments of Rhodes University.

#### *3.6.2.1 Inclusion Criteria*

Participants need to be comfortable underwater, currently apparently healthy, no acute or chronic impairment of fine motor performance either acute or chronic. Participants also require appropriate natural vision or corrected vision.

#### *3.6.2.2 Exclusion Criteria*

Participants who were not physically fit, could not swim, or did not meet the inclusion criteria were excluded from the study. If a participant is apparently healthy, however, due to an illness could be excluded. Participants who experienced a sense of claustrophobia were excluded due to the confined nature of the water tank. Participants with asthma were excluded from the study. Participants with a sensitivity

to chlorinated water were also excluded. Any participant with or recovering from injury within the past six months was excluded.

### 3.7 Experimental Setup

#### 3.7.1 Independent and Dependent Variables

The independent variables of the study were the equipment used, such as the breathing apparatus and dive mask, as well as water temperature. The water temperature was maintained to 32°C to eliminate the effects of being submerged in cold water.

The study's dependent variables were the participants' performance times in the fine motor function task and their performance in the Landolt-C visual acuity test, heart rate, and heart rate variability.

#### 3.7.2 Light Conditions

Lighting conditions changed throughout the testing procedure. Surface illumination was measured for all light levels and remained the same throughout testing in all turbidity conditions. Working depth illumination was measured for each light level and each water turbidity condition.

Table 3.2: Surface illumination levels and working depth illumination for testing conditions (in lux)

Water condition	Clear Water			Low Turbidity			Moderate Turbidity		
	Low	Medium	Bright	Low	Medium	Bright	Low	Medium	Bright
Light level									
Surface illumination (in lux)	548	1027	1646	548	1027	1646	548	1027	1646
Working depth illumination (in lux)	113	270	492	136	284	460	104	262	386

#### 3.7.3 Turbidity Conditions

Turbidity was created in the tank using Nestlé hot chocolate powder. This is comprised of many powders, including cocoa powder which creates a brown murky colour in

water when dissolved, and milk powder which leaves small particles in the water. Hot chocolate powder was chosen because the particle sizes will remain the same and is easily replicable in any subsequent study, as well as changing the water colour which replicates the colours of silt and sand in bodies of water.

The powder was analysed by the Rhodes University Geology Department using a MasterSizer to determine the size of the particles that would be in the water. The hot chocolate powder was dried at 45°C and screened through a 1mm sieve prior to being processed by the MasterSizer. The minimum particle size of the hot chocolate powder was 0.0100µm with the maximum particle size being 127µm.

#### 3.7.4 Equipment

A Polar T31 coded heart rate band (worn by the participant) and a Polar V800 fitness watch (strapped to the back plate) were used for all testing conditions underwater to measure heart rate variability (figure 3.3).



Figure 3.3 Polar V800 fitness watch (Left) and Polar T31 coded heart rate band (Right).

A stopwatch was used outside of the tank by the researcher to measure the performance times of the fine motor and visual acuity tests.

Participants were weighed down with a weight belt (figure 3.4) with enough weight to ensure submersion and contact with the floor of the tank without premature and involuntary ascension. The weight belt had a quick release mechanism in case of emergency, and a participant needed to ascend quickly.



Figure 3.4 Diving weight belt with quick release buckle.

SCUBA gear (figure 3.5) was used in the hydrostatic tank with the cylinder attached to a backplate and harness so it did not interfere with the participant while they completed the task while still simulating the working gear that dive operators use while underwater. The SCUBA gear consisted of a cylinder filled with compressed breathable air, first and second stages, a primary regulator, an emergency regulator (OCTO), as well as a submersible pressure gauge (SPG).



Figure 3.5 Diving equipment used for testing. 1- Backplate and harness; 2- SCUBA cylinder with first stage; 3- SPG; 4- regulator (second stage); 5- OCTO (second stage).

The equipment used for the task and task setup are lettered in Figure 3.3 and labelled below.

A – Table set at a comfortable working height.

B – Shape puzzle board (fine motor task).

C – SCUBA gear with first stage, an emergency regulator (OCTO) and a submersible pressure gauge.

D – Primary regulator.

E – Weight belt with lead weights.

F – Diving mask.

G – Backplate with harness straps that SCUBA cylinder is attached to.

H – Bag for the puzzle-shape board pieces.

I – Ladder for entry in and exit of the water tank.

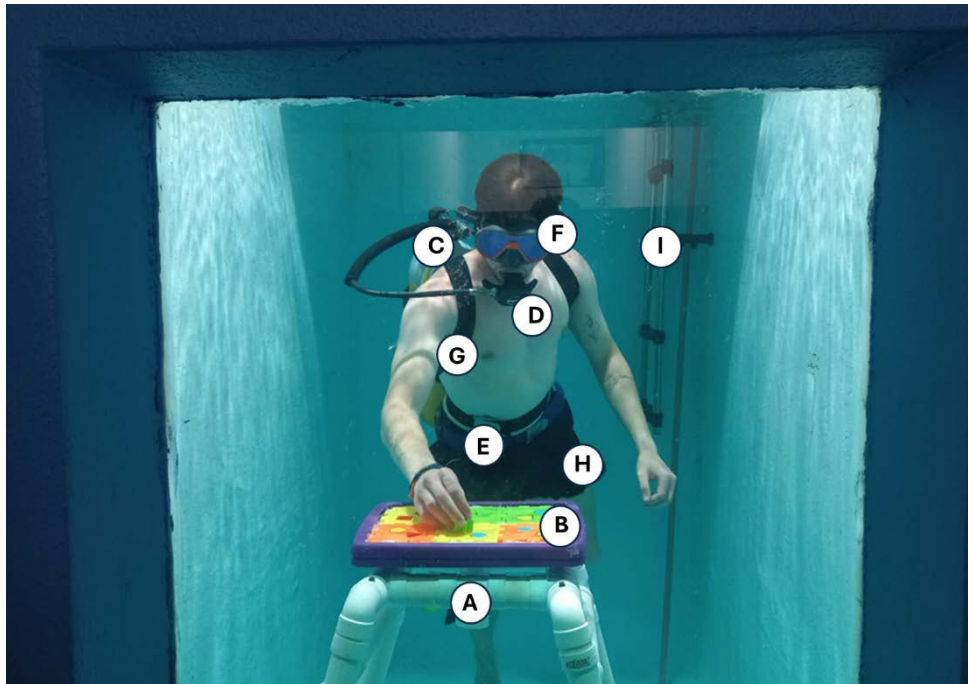


Figure 3.1: Fine motor testing setup from the researchers' view (clear water; bright light conditions)

### 3.7.5 Task Setup

The fine motor task (Figure 3.3), was a shape recognition puzzle that was fixed to a table at a suitable working height, eliminating the need for body posture bending. A bag was attached to participants' waists that contained all the shapes needed to complete the puzzle.

### **3.8 Experimental Procedure**

The experimental procedure consists of a total of four sessions, the information and habituation (session 1) and the turbidity and light condition testing sessions (sessions 2 to 4). Water conditions were changed between sessions 2, 3 and 4, increasing the turbidity (particle presence in the water) in each session. In each session, participants performed two separate tasks under three light conditions (bright, medium, or low light).

#### **3.8.2 Information and Habituation Session**

The first session was an information and habituation session in which the participant was given all the relevant information relating to their involvement in the study. Once all the information had been given to the participant and their questions had been answered to their satisfaction, they were given an informed consent form to read through and sign. After all the information had been given, and all questions had been answered, and the participants had the opportunity to sign the informed consent form.

The researcher recorded the participants weight indicated on a digital scale and their height. Once stature and mass had been recorded, participants had a chance to experience the clear underwater condition and become comfortable or familiarise themselves with using assisted breathing apparatus. During this session no other equipment was placed on the participant or in the tank other than the shape puzzle box.

#### **3.8.3 Turbidity and Light Testing Sessions**

The following sessions 2 – 4 were the light and turbidity condition testing sessions.

In each of the sessions, participants placed the Polar V800 heart rate monitor strap onto their chests. After which participants were helped into the backplate holding the SCUBA cylinder. A weight belt holding between four and six percent of the participant's weight was placed onto them. Finally, a strap holding a small and accessible bag containing the puzzle pieces for the fine motor task was placed onto the participant. A pre-dive safety check was conducted. The participant then partially submerged themselves and put their dive mask on, taking precautions so the mask would not fog

during testing. Once the participant was ready the researcher started the heart rate tracking on the fitness watch. Participants fully submerged themselves in the water and stood in front of the fine motor task. There was a one-minute period before the fine motor test began to ensure the participant was comfortable. This time also allows for the HRV analysis to exclude the first minute of the recording as this was not part of the testing protocol.

Participants then began the first fine motor task with the researcher starting the stopwatch. Once the fine motor task was complete the participant signalled to the researcher behind the glass of the tank that they were complete, and the time was stopped and recorded. Participants then had a two-minute period to gather the puzzle pieces from the fine motor task and place them back into the bag, after which the participant stood in front of the fine motor task ready for the next light condition. The light level was changed by the researcher during this time. After the two-minute period the next light condition test began with the same procedure as the first. This process was repeated the remaining light conditions. Once the fine motor task was completed under all light conditions the participant signalled to the researcher that they were comfortable.

Following this the visual acuity task would begin. The researcher recorded the total time taken up until this point to isolate the fine motor task time from the visual acuity task time. The light level was adjusted, and the visual acuity task began. Landolt-C rings were displayed one at a time from outside of the tank by the researcher and the responses were recorded. After 10 ring displays the light level was adjusted. This process was repeated until each of the light levels had been assessed and recorded. Once a total of 30 ring displays had been responded to, ten in each light condition the researcher recorded the total time once more and signalled to the participant that the testing session was complete.

The participant then moved towards the ladder in the tank and began to ascend. While the participant was half submerged the researcher stopped the HR recording on the Polar watch and helped the participant out of the tank. When participants were out of the water all the dive gear and equipment was removed.

Once participants were dry and comfortable they engaged in a short discussion with the researcher on how they felt each test went and what each condition was like, as well as some other informal questions to be recorded under experiment observations.

### **3.9 Data Reduction and Analysis**

Task performance times and visual acuity responses were recorded and placed into a Microsoft Excel spreadsheet. Total testing times and heart rate data were extracted from Polar FlowSync software. The time data was compared with the researcher's time stamps to isolate between the fine motor task and the visual acuity task. Once isolated, the HR data was split into each task and then imported into KUBIOS (version 4) software for HRV analysis. All the data was then summarised in Microsoft Excel spreadsheets as tables.

All of the performance and physiological data for the fine motor tasks were extracted from the collection software. Data was then cleaned and prepared for analysis using Microsoft Excel. The data was then analysed using R (R Core Team, 2024). A Shapiro-Wilk normality test (Shapiro & Wilk, 1965) using the `shapiro.test()` in the R base stats package. The data were found not to be normally distributed. An Aligned Rank Transform (ART) (Wobbrock et al., 2011) was conducted using the ARTool package in R (Kay et al., 2025), followed by an ANOVA. Where significant differences were found, a post-hoc analysis was conducted using a pairwise comparison of estimated marginal means with a Tukey adjustment, using the `emmeans()` R package (Lenth et al., 2025; Searle et al., 1980).

All analyses were conducted without experience as a covariate, and it was found that underwater experience did not increase the explained variance.

All performance and physiological data for the visual acuity tasks were extracted from the collection software, imported into Microsoft Excel 365, cleaned and structured. Statistical analyses were conducted using R version 4.3.1 (R Core Team, 2024). All data were tested for normality using a Shapiro-Wilk test (Shapiro & Wilk, 1965) via the `shapiro.test()` in R base stats package. The data that violated the assumptions for normality were analysed using a Friedman ANOVA, via the `friedman_test()` function in the R base stats package. Where significant differences were found, a post-hoc

Wilcoxon Matched Pairs Test was conducted using the `pairwise_wilcox_test()` function in the `rstatix` library (Kassambara, 2023).

All data that were found to be normally distributed were analysed using an ANOVA, via the `aov()` function in R base stats.

All analyses were conducted without experience as a covariate, as it was found that underwater experience did not increase the explained variance.

HRV data was analysed using Kubios software. Data is displayed using Microsoft Excel, graphing the data as means with standard deviation (SD) error bars.

## **Chapter 4 Results**

### **4.1 Introduction**

This chapter presents the data collected from the fine motor task and visual acuity task designed to assess the effects of turbidity and light levels on human fine motor performance and visual acuity underwater. Participants completed the puzzle board and Landolt-c visual acuity test in three water conditions (clear water, low turbidity, and moderate turbidity) and three light levels (low, medium and bright light).

### **4.2 Participant Characteristics**

Twelve Males and six females (n=18), with a mean age of 23 ( $\pm$  3) years participated in the study. All participants were comfortable in and around water. There were no exclusionary criteria for lack of scuba diving experience. Ten participants had scuba diving experience, one participant had underwater experience from a previous underwater study, and seven participants had never used scuba apparatus before.

All participants had habituation sessions until they were comfortable underwater. All inferential statistics were calculated with and without experience as co-variate. However, underwater experience did not increase the explained variance. Therefore, in the following sections, the analyses without using experience as a co-variate are presented.

### **4.3 Fine Motor Task**

The fine motor task required participants to complete a shape puzzle board, placing the appropriate shape into the corresponding slot as fast as possible. Time to completion was assessed as an indicator of performance. Participants had to complete the shape puzzle board in three water conditions and three light conditions.

### 4.3.1 Fine Motor Task Performance Results Overview

Table 4.1 Fine motor performance times overview: Mean performance time in seconds; Standard deviation and Coefficient of variation percentage

Water Condition Light levels	Clear Water			Low Turbidity			Moderate Turbidity		
	Low	Medium	Bright	Low	Medium	Bright	Low	Medium	Bright
Mean (seconds)	44.59	42.93	40.25	41.06	38.18	38.90	40.67	39.34	38.52
St. Dev	7.74	9.79	7.06	6.29	5.11	8.12	5.01	6.45	6.36
CV%	17.35	22.80	17.53	15.32	13.38	20.88	12.32	16.40	16.51

### 4.3.1 Task Performance

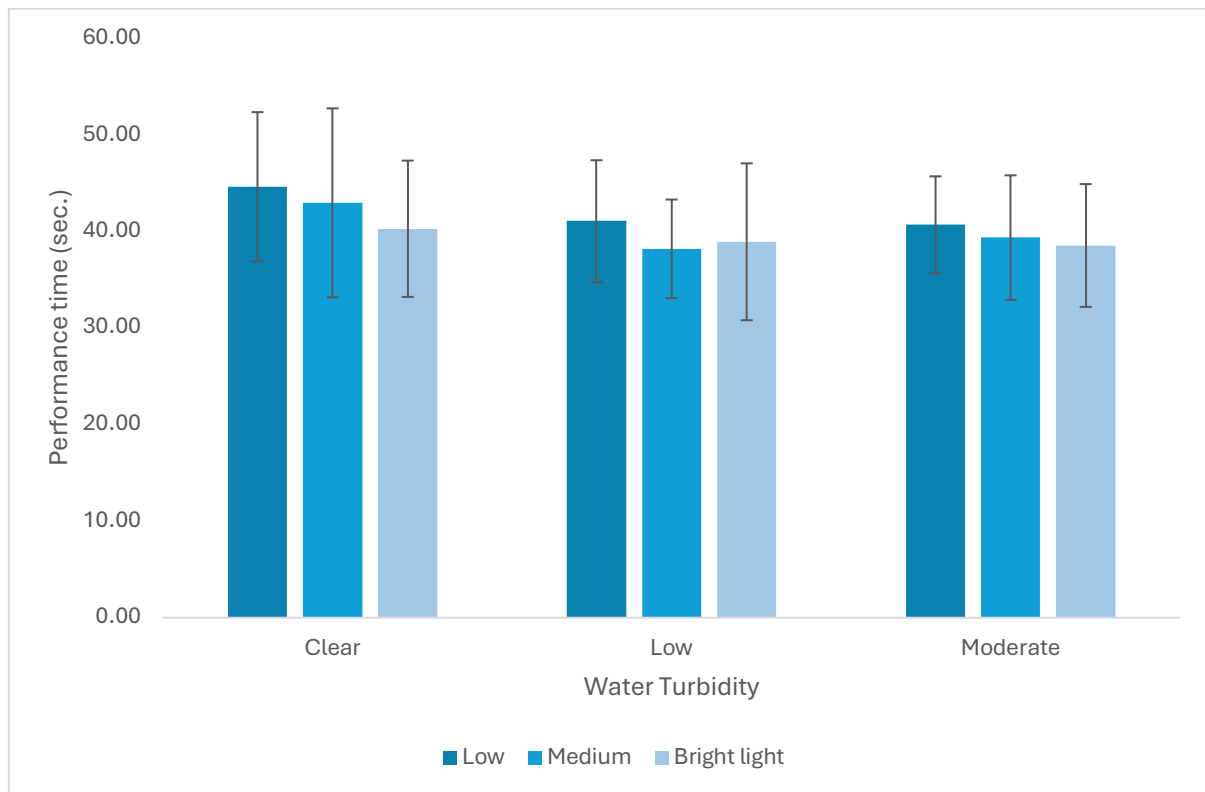


Figure 4.1: Mean ( $\pm$ SD) performance times of the fine motor task

Performance times change across the three water conditions and the three light levels. Performance times decreased slightly from the clear water conditions across all light levels (figure 4.1) There is a slight difference in performance times between the two turbid water conditions.

Table 4.2 Repeated measures analysis of variance for performance times of the fine motor task (Asterisk\* shows statistical significance ( $p < 0.05$ ))

Factor	Degr. Of Freedom	F	p
Turbidity	2, 136	6.95097	0.00133584*
Light	2, 136	7.34348	0.00093648*
Turbidity x Light	4, 136	0.41702	0.79614641

Table 4.2, the ANOVA of aligned rank transformed data shows there was a significant difference between performance times between the light levels and the turbidity conditions, however, there was no interactional effect between conditions on fine motor performance time. Further analysis through a Tukey post-hoc test there was a difference between the clearwater condition and the low and moderate turbidity conditions. The Tukey post hoc test also showed a difference between low-light conditions and medium and bright light conditions (Appendix D1).

#### 4.3.2 Heart Rate Variability

Heart rate and heart rate variability (HRV) were analysed in the frequency and time domain. They were analysed, but there is no statistical significance in any measures or parameters of interest that would determine psychophysiological responses to stress and or recovery. All these factors share the same trend. The results of all other HRV measures are reported in Appendix C.

Mean HR is the mean number of beats per minute (bpm) throughout the duration of the task. SDNN is the standard deviation of normal-to-normal RR intervals calculated for short time periods (3 min to 10 min). RMSSD is the square root of mean squared differences of consecutive NN intervals, this is the measure of high frequency (HF)

HRV. pNN50 is the percentage of differences of RR intervals greater than 50ms. This percentage is taken from NN50 which is the number of normal RR intervals where the difference is greater than 50ms. Frequency domain measures were analysed in the AR-based spectral analysis as this method is better at analysing shorter time frames. Low frequency (LF, 0.04 – 0.15 Hz) High frequency (HF, 0.15 – 0.4 Hz), and R is the ratio of LF to HF (LF/HF).

Table 4.3 shows the HRV measures taken from the fine motor task. The fine motor task HRV was assessed for each of the light conditions and each of the water turbidity conditions. This was to analyse how working underwater in the presence of turbidity may be affected by differing light levels from an artificial light source.

Table 4.3: Heart rate variability measures for fine motor task

RR (Hz)	No turbidity			Low turbidity			Moderate turbidity		
	Clear	Medium	Bright	Clear	Medium	Bright	Clear	Medium	Bright
Mean HR (bpm)	93 ± 15	93 ± 15	95 ± 16	92 ± 16	92 ± 21	91 ± 18	88 ± 11	90 ± 12	86 ± 13
SDNN (ms)	215 ± 213	133 ± 122	217 ± 273	176 ± 206	176 ± 291	129 ± 143	175 ± 176	143 ± 130	229 ± 204
RMSSD (ms)	236 ± 281	231 ± 296	152 ± 193	219 ± 279	220 ± 422	157 ± 224	230 ± 268	177 ± 180	274 ± 276
pNN50 (%)	20 ± 16	17 ± 14	22 ± 22	22 ± 22	22 ± 28	24 ± 26	21 ± 20	18 ± 16	24 ± 20
LF (n.u)	62 ± 26	55 ± 23	57 ± 20	54 ± 22	53 ± 19	59 ± 21	61 ± 22	51 ± 24	60 ± 21
HF (n.u)	38 ± 26	45 ± 22	43 ± 20	46 ± 22	47 ± 19	41 ± 21	39 ± 22	49 ± 24	40 ± 21
R	4 ± 3	3 ± 5	3 ± 4	2 ± 2	2 ± 2	3 ± 4	3 ± 3	2 ± 2	3 ± 3

Table 4.4 shows the repeated measures ANOVA of aligned rank transformed data for SDNN (Standard deviation of NN intervals) measurements from the fine motor task across the three water conditions (clear water, low turbidity, and moderate turbidity) and the three light levels (low, medium, and bright light). There was no statistical

significance in SDNN for the turbidity and light factors, nor was there any interactional effect.

Table 4.4: Repeated measures analysis of variance of SDNN for the fine motor task (Asterisk\* shows statistical significance ( $p < 0.05$ ))

Factor	Degr. Of Freedom	F	p
Turbidity	2, 136	2.0917	0.12743
Light	2, 136	1.5415	0.21777
Turbidity x Light	4, 136	0.7264	0.57537

The table below (table 4.5) shows the repeated measures ANOVA of aligned rank transformed data for RMSSD (root mean square of successive differences) measurements from the fine motor task across the three water conditions (clear, low turbidity, and moderate turbidity) and the three light levels (low, medium, and bright light). There was no statistical significance in RMSSD for the fine motor task.

Table 4.5: Repeated measures analysis of variance of RMSSD for the fine motor task (Asterisk\* shows statistical significance ( $p < 0.05$ ))

Factor	Degr. Of Freedom	F	p
Turbidity	2, 136	1.86993	0.15808
Light	2, 136	0.55454	0.57563
Turbidity x Light	4, 136	0.62992	0.64197

#### 4.4 Visual Acuity Task

Performance measures of visual acuity assessed the factors of performance time and correct responses. Performance time is the time taken to display the correct direction of the Landolt-c ring opening that was displayed from behind the window of the under-

water tank. The number of C-rings that were displayed totalled thirty per turbidity condition, with ten C-rings per light condition. The correct responses were recorded and analysed. The number of errors is the inverse of the number of correct responses.

#### 4.4.1 Visual Acuity Results Overview

Table 4.6 Performance times overview for the visual acuity task: Mean performance time in seconds; Standard deviation and Coefficient of variation percentage

	Turbidity condition		
	Clear	Low	Moderate
Mean	251.67	132.67	115.17
St. dev	98.98	46.39	56.89
CV%	39.33	34.97	49.40

Table 4.7 Correct response overview for the visual acuity task: Mean number of correct responses; Standard deviation and Coefficient of variation percentage

	Turbidity condition		
	Clear	Low	Moderate
Mean	29.33	26.61	24.06
St. dev	1.08	2.95	6.38
CV%	3.70	11.10	26.50

Table 4.8 Correct response per minute overview for the visual acuity task: Mean number of correct responses per minute; Standard deviation and Coefficient of variation percentage

	Turbidity condition		
	Clear	Low	Moderate
Mean	8.21	13.46	14.98
St. dev	3.54	4.90	6.79
CV%	43.13	36.42	45.29

Table 4.9 Number of errors overview for the visual acuity task: Mean number of errors; Standard deviation and Coefficient of variation percentage

	Turbidity condition		
	Clear	Low	Moderate
Mean	0.67	3.39	5.94
St. dev	1.08	2.95	6.38
CV%	162.70	87.15	107.25

Table 4.10 Number of errors per minute overview for the visual acuity task: Mean number of errors per minute; Standard deviation and Coefficient of variation percentage

	Turbidity condition		
	Clear	Low	Moderate
Mean	0.28	1.83	3.25
St. dev	0.54	1.80	3.26
CV%	193.08	98.22	100.33

#### 4.4.2 Performance Time

The visual acuity task required participants to complete a Landolt-c visual acuity test. Participants were required to point or tap the glass of the observation window in the direction of the opening of the 'C' that was displayed to them. There were three water conditions and three light conditions that the Landolt-c visual acuity test had to be completed in.

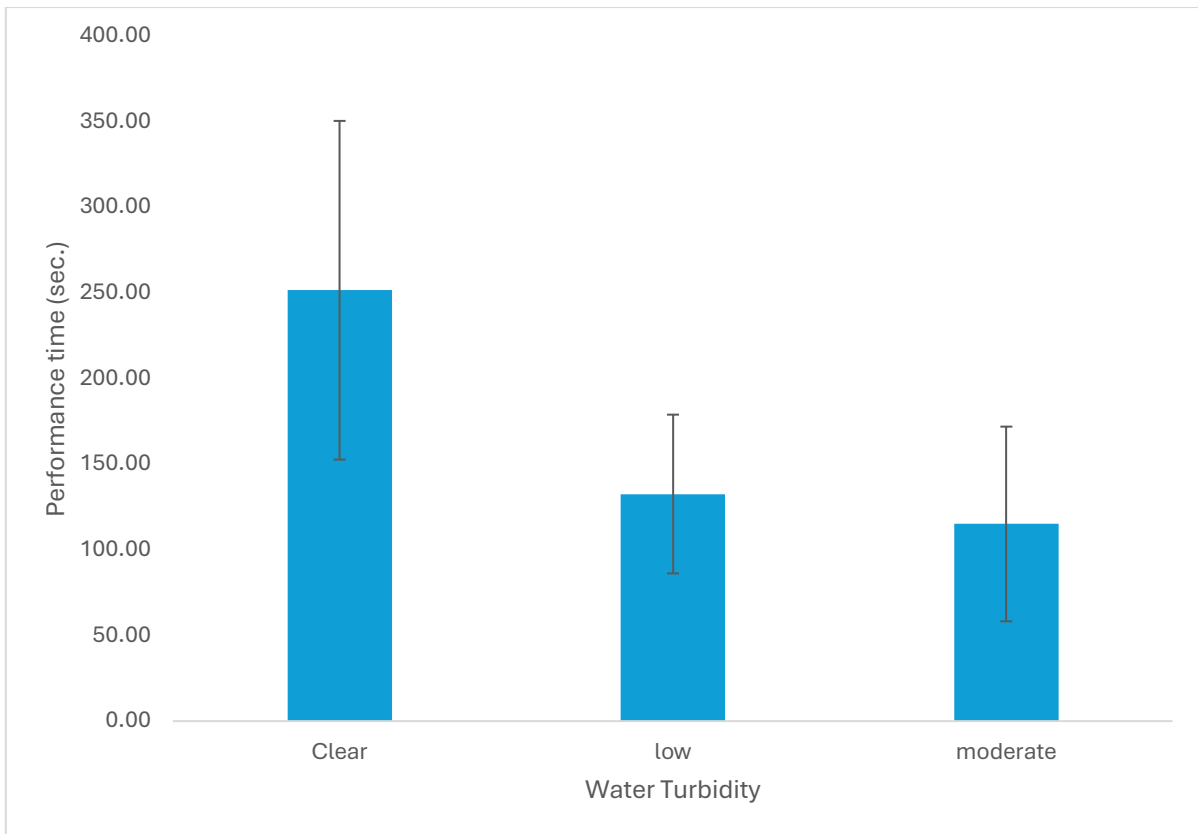


Figure 4.2: Mean ( $\pm$ SD) performance times of the visual acuity task

Performance times decreased significantly from the clear water conditions with changing light levels. There is a slight difference in performance times between the two turbid water conditions (Figure 4.2).

Performance times differ significantly between the water turbidity conditions (Table 4.11). A Friedman test revealed a significant effect of turbidity on performance time,  $\chi^2(2)=18.10$ ,  $p < 0.001$ .

Post-hoc pairwise Wilcoxon signed-rank tests with Holm correction indicated that performance times were significantly faster in clear water compared to both low turbidity ( $p < .001$ ) and moderate turbidity ( $p < .001$ ). However, there was no significant difference between low and moderate turbidity ( $p = .107$ ).

Light was not a measured factor for this analysis. This task was meant to simulate underwater work in different levels of turbidity with changing light levels similar to real-world light changed from the surface.

Table 4.11: Repeated measures analysis of variance of the performance times for the visual acuity task in changing turbidity conditions (Asterisk\* shows statistical significance ( $p < 0.05$ ))

Factor	Degr. Of Freedom	$\chi^2$	p
Turbidity	2	18.10	0.000117*

#### 4.4.3 Visual acuity response

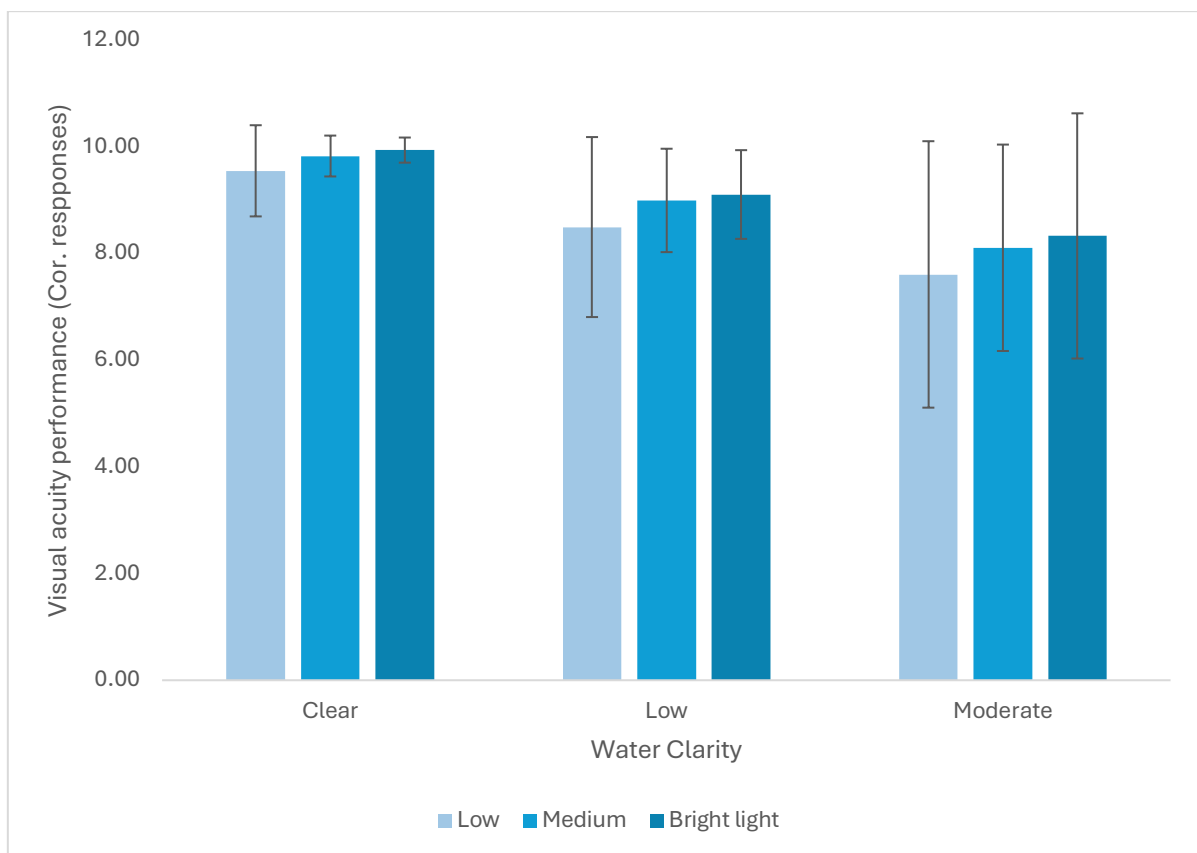


Figure 4.3: Number of correct responses ( $\pm$ SD) for the visual acuity task

From the ten visual displays per light level and 30 total visual displays per water condition, figure 4.3 shows that there is an increase in visual acuity performance as light levels increase from low light to bright light across all the water turbidity conditions. There is also a decrease in correct responses as water turbidity increases. Standard deviation increases in visual acuity performance as water turbidity increased.

Table 4.12: Repeated measures analysis of variance of correct responses for the visual acuity task (Asterisk\* shows statistical significance ( $p < 0.05$ ))

Factor	Degr. Of Freedom	$\chi^2$	p
Turbidity	2	25.10	0.00000348*

A Friedman test indicated a significant effect of turbidity on correct responses,  $\chi^2(2) = 25.10, p < .001$ . (table 4.12).

Post-hoc Wilcoxon signed-rank tests with Holm correction showed that participants made significantly more correct responses in clear water compared to both low turbidity ( $p = .001$ ) and moderate turbidity ( $p < .001$ ). No significant difference was found between low and moderate turbidity ( $p = .059$ ).

#### 4.4.4 Response Rate

The response rate is the number of correct responses, and the number of errors produced each minute under each condition. This was analysed to understand how many errors can occur while working in real-world simulated conditions.

#### 4.4.4.1 Success Rate

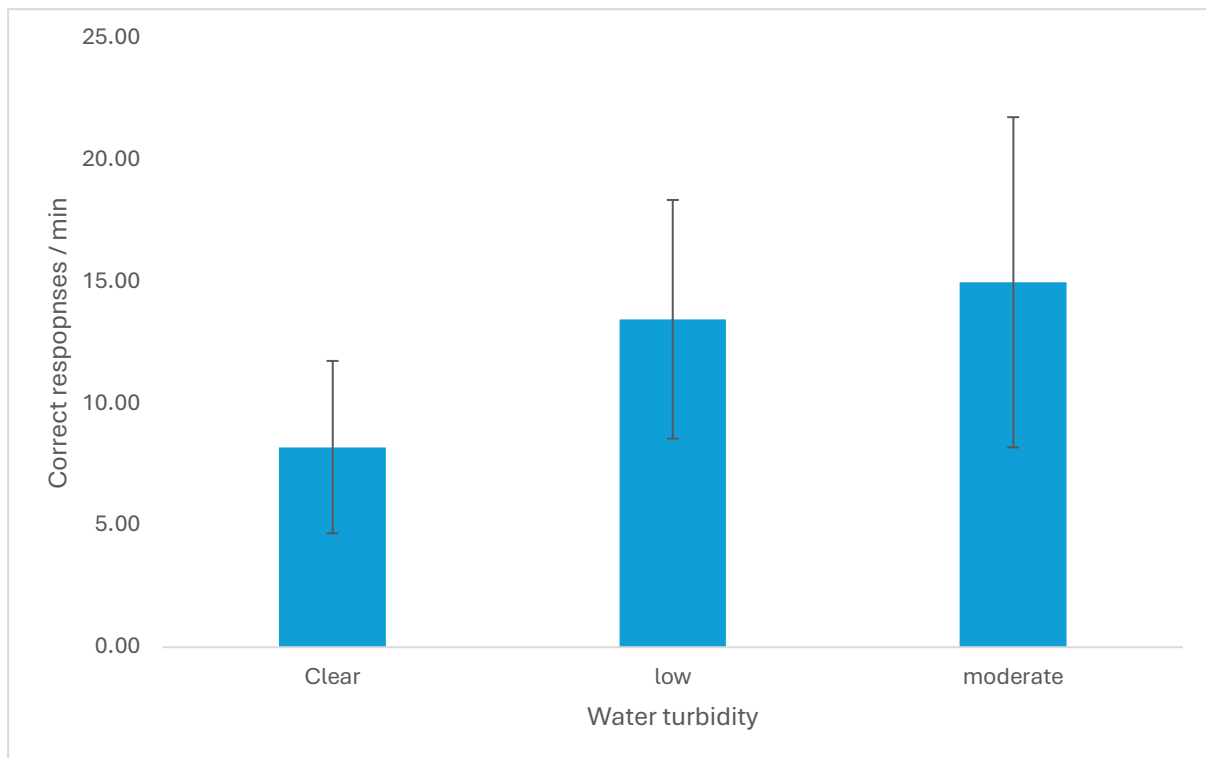


Figure 4.4: Mean ( $\pm$ SD) number of correct responses per minute for the visual acuity task

There is a linear increase in correct responses per minute as there is an increase in water turbidity (figure 4.4), however as water turbidity increases there is greater deviation in the number of correct responses per minute.

#### 4.4.4.2 Error Rate

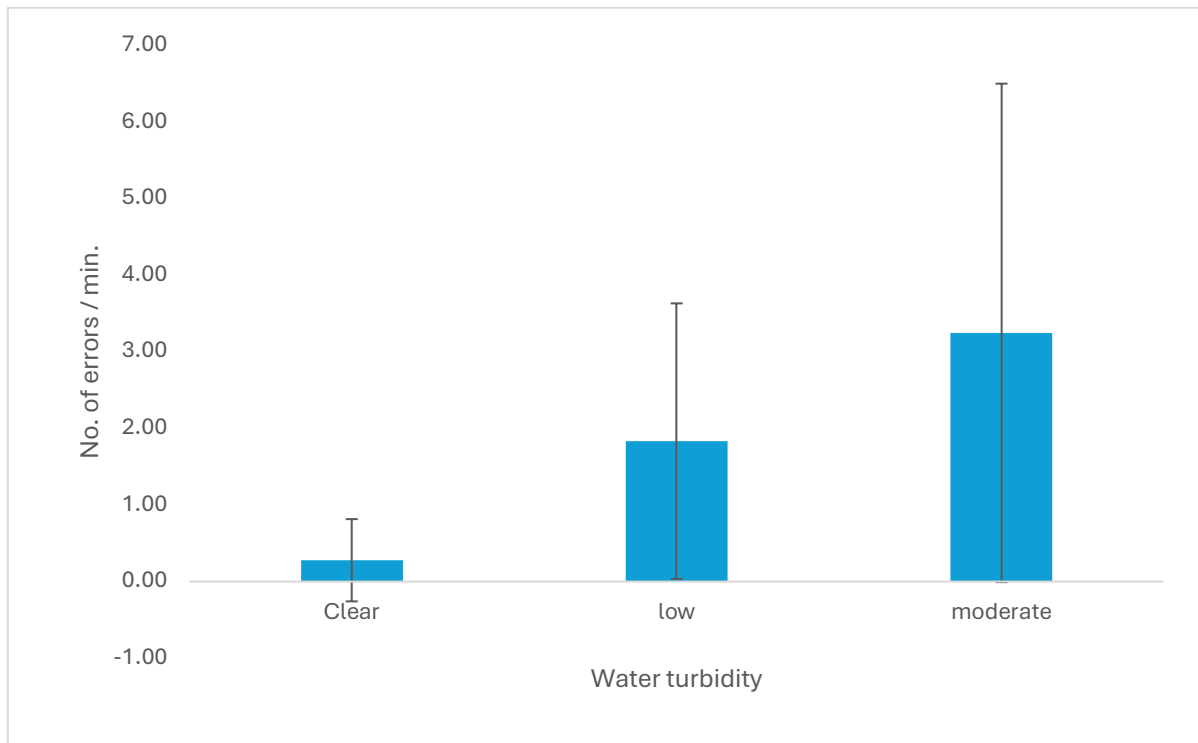


Figure 4.5: Mean ( $\pm$ SD) number of errors/ minute for the visual acuity task

There is a linear increase in errors per minute as water turbidity increases. With this increase in errors per minute there is also a substantial increase in standard deviation as water turbidity increases (figure 4.5).

#### 4.4.5 Heart Rate Variability

Heart rate and heart rate variability (HRV) were analysed in the frequency and time domain. We have tested and analysed all heart rate factors for the task. There was no significance in any factors of interest that would determine physiological responses to stress and or recovery. All these factors share the same trend. The results of all other HRV measures are recorded in Appendix C.

Mean HR is the mean number of beats per minute (bpm) throughout the duration of the task. SDNN is the standard deviation of normal-to-normal RR intervals calculated for short time periods (3 min to 10 min). RMSSD is the square root of mean squared differences of consecutive NN intervals, this is the measure of high frequency (HF) HRV. pNN50 is the percentage of differences of RR intervals greater than 50ms. This

percentage is taken from NN50 which is the number of normal RR intervals where the difference is greater than 50ms. Frequency domain measures were analysed in the AR based spectral analysis as this method is better at analysing shorter time frames. Low frequency (LF, 0.04 – 0.15 Hz) High frequency (HF, 0.15 – 0.4 Hz), and R is the ratio of LF to HF (LF/HF).

Table 4.13: Heart Rate Variability for Visual Acuity Task

RR (Hz)	Turbidity		
	Clear	Low	Moderate
Mean HR (bpm)	86 ± 13	89 ± 13	87 ± 11
SDNN (ms)	276 ± 253	168 ± 165	219 ± 243
RMSSD (ms)	373 ± 378	221 ± 245	282 ± 347
pNN50 (%)	21 ± 13	21 ± 23	21 ± 20
LF (n.u)	62 ± 18	57 ± 19	61 ± 17
HF (n.u)	38 ± 18	43 ± 19	39 ± 17
R	2 ± 2	2 ± 1	2 ± 2

Table 4.13 shows the HRV measures taken from the visual acuity task. HRV was analysed for the turbidity conditions with changing light levels. Light levels were not assessed individually. This was to simulate a real-world scenario where a diver may be working in the presence of water turbidity with changing light levels from the surface.

Table 4.14: Repeated measures analysis of variance of SDNN for the visual acuity task (Asterisk\* shows statistical significance (p<0.05))

Factor	Degr. Of Freedom	X <sup>2</sup>	p
Turbidity	2	1.44	0.486

There was no statistical significance in SDNN factors for heart rate variability during the visual acuity task, indicating that turbidity does not change stress levels in humans while underwater (table 4.14).

Table 4.15: Repeated measures analysis of variance of RMSSD for the visual acuity task (Asterisk\* shows statistical significance ( $p < 0.05$ ))

Factor	Degr. Of Freedom	$\chi^2$	p
Turbidity	2	1.33	0.513

There was no statistical significance in RMSSD during the visual acuity task (Table 4.15).

## 4.5 Results Overview

Table 4.16 Results overview for fine motor tasks and visual acuity task and interaction effects between conditions on fine motor performance and visual acuity

Factor	Fine motor task		Visual acuity	
	Performance	HRV	Performance	HRV
<b>Turbidity</b>	With increased turbidity, performance times decreased.		With increased turbidity, performance times decreased.	
<b>Light</b>	With decreased light levels, performance time decreases		With decreased light levels: <ul style="list-style-type: none"> <li>● The number of correct responses decrease</li> <li>● Number of errors increase</li> <li>● Number of cor. Responses/ minute decrease</li> <li>● Number of errors/ minute increase</li> </ul>	
<b>Turbidity * light</b>				

Table 4.16 indicates the significant differences in performance for both the fine motor task and the visual acuity task in each of the turbidity and light conditions. Blank spaces in the table indicates that there was no significant difference between conditions or tasks.

## Chapter 5 Discussion

### 5.1 Introduction

This chapter expands and explains the findings and analyses from the results section (Chapter 4). The primary objective of this chapter is to discuss the outcomes of the testing procedures and conditions and, finally, to respond to the hypothesis' assumptions.

The analysis conducted in this study for the fine motor tasks saw that all the performance and physiological data were extracted from the collection software. Data was then cleaned and prepared for analysis using Microsoft Excel. Data was then analysed using R (R Core Team, 2024). A Shapiro-Wilk normality test (Shapiro & Wilk, 1965) using the `shapiro.test()` in the R base stats package. The data were found not to be normally distributed. An Aligned Rank Transform (ART) was conducted (Wobbrock et al., 2011; Kay et al., 2025), followed by an ANOVA. Where significant differences were found, a post-hoc analysis was conducted using a pairwise comparison of estimated marginal means with a Tukey adjustment, using the `emmeans()` R package (Lenth et al., 2025; Searle et al., 1980). All analyses were conducted without experience as a covariate, and it was found that underwater experience did not increase the explained variance.

For the analysis of the visual acuity tasks all performance and physiological data were extracted from the collection software, imported into Microsoft Excel 365, cleaned and structured. Statistical analyses were conducted using R version 4.3.1 (R Core Team, 2024). All data were tested for normality using a Shapiro-Wilk test (Shapiro & Wilk, 1965) via the `shapiro.test()` in R base stats package. The data that violated the assumptions for normality were analysed using a Friedman ANOVA, via the `friedman_test()` function in the R base stats package. Where significant differences were found, a post-hoc Wilcoxon Matched Pairs Test was conducted using the `pairwise_wilcox_test()` function in the `rstatix` library (Kassambara, 2023). All data that were found to be normally distributed were analysed using an ANOVA, via the `aov()` function in R base stats. All analyses were conducted without experience as a covariate, as it was found that underwater experience did not increase the explained variance.

. The analysis focused on the water conditions of each task; no turbidity, low turbidity and moderate turbidity, as well as the light levels of each task; low, medium and bright light.

A change in performance times was expected between light conditions and water turbidity conditions. The changes in light levels from low to bright light were thought to make the tasks easier, while the changes in water turbidity from clear to moderate turbidity were expected to make the task more difficult. In this regard, it is assumed that due to increased difficulty from the water conditions, light levels can be increased to make a task easier. Heart rate variability was used to determine the physiological effects of each task and their conditions to determine changes in autonomic responses to conditions to determine if a certain task was more difficult than another. Physiological condition effects were expected to be identified using heart rate variability factors.

This discussion will focus on the task conditions and their effects on visual acuity and fine motor performance, as well as the physiological responses to each task.

## **5.2 Response to Hypotheses**

A statistical analysis of variance and Tukey post-hoc test led to the following responses to the hypotheses:

### **5.2.1 Task Performance**

There was an expectation that the performance of the fine motor task would be different between the three lighting conditions. The bright light condition was significantly different to the low and medium light conditions. There was no significant difference between low light conditions and medium light conditions.

The performance of the fine motor task was expected to be different between the three lighting conditions. There was a significant difference between all turbidity conditions.

The performance for the visual acuity task was expected to be different between the three different light conditions. A significant difference was found between turbidity conditions for the number of correct responses. A significant difference was found

between turbidity conditions for performance times. Finally, a significant difference was found between turbidity conditions and the number of correct responses per minute.

### 5.2.2 Heart Rate Variability

Heart rate variability was expected to differ between the three lighting conditions and the three turbidity conditions. There was no significant difference found between the conditions.

### 5.2.3 Interactional Effects

#### 5.2.3.1 Task Performance

It was expected that there would be an interactional effect between the lighting conditions and the turbidity conditions. There was no significant difference between the lighting conditions and the turbidity conditions. There was no interactional effect.

#### 5.2.3.2 Heart Rate Variability

It was expected that there would be an interactional effect between the lighting conditions and the turbidity conditions on heart rate variability. There was no significant difference found between the conditions. There was no interactional effect.

## 5.3 Condition Effects

Task performance effects were found in both the visual acuity and fine motor task in the presence of turbidity and light level changes. The turbidity effects on task performance that were found were between the clear water and the turbid water conditions (low and moderate turbidity). There was no difference between the turbid water conditions. There were visual acuity task effects found between the light level conditions and the water turbidity conditions, indicating that visual acuity performance is affected by environmental conditions. There was a significant difference in both visual acuity task speed and responses.

There was an expectation that task performance would worsen as water conditions became more difficult but made easier with the use of increasing light levels, and this will be discussed further throughout this section. The conditions will be explained and expanded on regarding each task that was performed throughout the study.

### 5.3.1 Performance during the Fine Motor Task

Fine motor tasks are used widely during underwater operations, mainly for adjusting diving gear and equipment to function optimally. Fine motor function is also used during certain tasks that require discrete or precise movements, such as welding or fastening. This section expands on how the testing conditions affected fine motor function during the testing protocol.

Fine motor task performance times improved throughout the study despite the increase in water turbidity. As turbidity increased, the performance times decreased. Performance times were the longest during the clear water sessions and shortest during the moderate turbidity sessions. There was a significant difference in performance times between the clear water sessions and the subsequent turbidity sessions, however, there was no significant difference in performance times between the low and moderate turbidity sessions. When investigating further, the standard deviations in performance times across all water conditions show that there is a greater standard deviation in the clear condition, with the least standard deviation being displayed during the moderately turbid water condition. This was an unexpected result but could be a consequence of one of the limitations of the study being that turbidity was to increase gradually over each session. Water turbidity levels increased from sessions two to four rather than being permuted. This was a limitation of the study that was known before testing started due to the current water availability situation in Makhanda. This situation meant that the testing tank could not be drained and filled again in a timely manner due to water shortages in the area. However, the increase in performance may also be a result of the learning effect and increased comfortability with the testing setup, this also shows that with increased experience and familiarity with a task performance improved irrespective of condition (Makinen et al., 2006; Sigrist et al., 2013). The decrease in performance time as turbidity increases

can also be attributed to fewer external environmental stimuli distractions (Baddeley, 2000; Weltman & Egstrom, 1966).

The improvement in performance times of the fine motor task can possibly be explained by the spotlight metaphor. In a paper published in 1999, Fernandez-Duque and Johnson describe a spotlight metaphor for the interpretation of images of attention studies. This metaphor describes a spotlight that is 'shone' over a larger image that guides and focuses attention on a particular point. In this paper they discuss that metaphors like this have a central role in scientific discoveries for human attention as these metaphors can expose hidden assumptions behind various research strategies (Fernandez-Duque & Johnson, 1999). Much like the assumption of this thesis, it was expected that performance would decrease for the fine motor task, however, performance increased, and it may be easy to assume that this increase in performance time was due to the motor learning effect, but through the spotlight metaphor more can be understood as to how humans can operate underwater in turbid conditions.

This spotlight metaphor can describe how the presence of turbidity in water allows the dive operator to focus on a particular area and identify images within their direct field of view without peripheral stimuli to distract from the task in front of them. This can explain why performance times decreased as turbidity increased in this thesis study, and with the presence of light being emitted into the water from above the area in direct view of the participants aided in their performance. This shows that both turbidity and light levels affect performance. However, these factors may affect performance separately, and more research needs to be conducted to determine exactly how they individually influence human fine motor performance underwater.

With the addition of light, there was a decrease in task performance time. The best performance times occur in bright light conditions apart from the low turbidity conditions. In this condition, medium light showed the best performance time. The worst performance time occurred in clear water with low light. There is a linear trend that shows that as light levels are increased, there is a decrease in performance time. This can indicate that even in the presence of turbidity or reduced visual contrast from environmental conditions underwater, the increase of light levels can aid in improving fine motor performance when working underwater.

The largest standard deviation in performance time occurs in clear water with a medium light level, and the least amount of deviation occurs in the low turbidity condition with a medium light level. This result shows that in the presence of turbidity, a dive operator can increase the light level in which they are working to improve performance due to the 'interrelatedness of sensuous perceptions underwater' (Merchant, 2011).

Looking at the interactions between light levels and turbidity the following can be said. There is no significant interactional effect between light levels and turbidity. It can be said that in turbid water conditions, a dive operator must use a light source to assist them in performing their task. This can change depending on the work that the operator is doing. If the operator is performing a visual inspection, it may be difficult to see clearly if their task is far away from them. If the operator is close to their task, they can use a light to illuminate the area and perform their task. There is a linear relationship between light levels and performance. As light increases performance times decrease. As turbidity increased performance times decreased. While the use of light helps with a fine motor task there are other factors to consider like fine motor function and proprioceptor feedback from the hands and fingers. This feedback and learning the feeling of the shapes for the puzzle may contribute more to performance than one's ability to see thus to improved performance as turbidity increases. A weakness from the start that might have led to learning effects was the inability to permute the various turbidity conditions. In order to avoid this, the study used a task that was very familiar to the participants, allowing them to practice while still assuming that their motor learning skills had already reached the point of a performance plateau. It must still be noted that the learning effect superimposes on the effects of turbidity during the experiment. It may also be possible to think that as turbidity increases and there is less reliance on vision, then the person subconsciously focuses on the feeling of the puzzle piece or that there is less distraction from the external environment so focus can be placed solely on the task in front of the operator, as explained by the spotlight metaphor (Fernandez-Duque & Johnson, 1999). The only other issue is that they will have to see where to put the piece into the puzzle but when there is reduced stimuli from the periphery, then the sole focus can be directed towards the direct field of view. This can be explained by perceptual narrowing, where diving in a 'dangerous' setting can contribute to decreases in performance. Weltman and Ergstrom (1966) described

that when diving in dangerous or unfamiliar conditions, tasks central to a diver do not interfere with peripheral tasks, as there is a subconscious desire to reduce the risk to themselves. In this study, there was 'near constant' performance on the central tasks while increasing response times to their peripheral task. Now, by using the spotlight metaphor as a means to understand the effects of turbidity and light levels on human performance in this study, combined with the knowledge that there is near constant central performance with increased periphery response times that Weltman and Ergstrom found in 1966. It could be explained that the increased performance times of the fine motor task were due to the seemingly dangerous conditions that turbidity produces while turbidity also acts like a natural spotlight reducing peripheral stimuli which in turn can improve performance.

### 5.3.2 Performance during the Visual Acuity Task

Visual acuity is necessary for dive operators in order to maintain situational awareness as there is no other source of sensory feedback from the environment other than vision. Visual acuity is vital in certain tasks underwater including looking at pressure gauges and other dive gear, as well as for certain tasks such as inspection work. This section expands on how the testing conditions influenced visual acuity during the testing protocol.

The Landolt-C visual acuity task was performed in all water conditions under changing light conditions with a focus being on the water turbidity conditions with changing light levels, simulating work that dive operators might experience while working underwater. Performance times include all three light levels, while accuracy (number of errors and correct responses) takes into consideration the water turbidity levels as well as each of the three light levels (low, medium and bright light).

Unexpectedly, performance times of the visual acuity task decreased significantly as water turbidity increased. The water condition with the longest performance time was the clear condition, while the shortest performance time was recorded during the moderately turbid water condition. There was a large deviation in performance times in the clear water condition, with the least amount of deviation occurring in the low turbidity condition. A possible explanation of this may be that the Landolt-C visual acuity test was not performed fully during the habituation session, and certain

participants may not have been familiar with this test, while others were familiar. This means that the participants who were familiar with the test did not have to process the visual information for as long as the participants who were unfamiliar. Performance times decreasing as turbidity increased may be explained by the fact that participants were unable to see the C-ring that was displayed confidently, and they simply guessed the direction of the opening, thus decreasing performance times. This is backed up by the number of correct and erroneous responses throughout the water conditions of this study.

It is evident that there was a significant difference in the number of correct and erroneous responses between water conditions. As water turbidity increases, the number of correct responses decreases, and the number of errors increases. The least number of errors occurred in the clear water condition. The greatest number of errors occurred in the moderately turbid water condition. The interaction between light levels and turbidity shows significant differences. As light levels increase, the number of correct responses increase, in turn, the number of errors decreases.

The condition with the best performance was clear water with bright light, while the condition with the worst performance was the moderate turbidity condition with low light levels.

When investigating the error rate across the water turbidity conditions, the number of errors per minute increases as water turbidity increases; however, there is a large amount of standard deviation in results, possibly due to familiarity. Interestingly, the number of correct responses per minute also increased as water turbidity increased, although with less deviation than the number of errors. It must be noted that these results do not consider the response rate for each light level but rather the response rate in water clarity conditions with changing light levels, simulating what a diver might experience while operating underwater.

The results of this thesis study can be compared with a study that was conducted on the effects of turbidity on harbour seal visual acuity in 2006 by Weiffen *et al.* In this study the visual acuity of harbour seals decreased dramatically with the increased presence of water turbidity (Weiffen *et al.*, 2006). In this 2006 study, the water was not changed in order to accumulate algae and other particulates within the water to increase turbidity, and the water depth was set at 1.3 meters. These conditions were

similar to the conditions studied in this thesis. Although this study investigated the effects of visual acuity on aquatic mammals the results are consistent with the decrease in visual acuity performance in humans that was identified in this thesis.

While there was a significant difference in results for both visual acuity performance time and responses, there was no significance in the interactional effect between light levels and turbidity on human visual acuity.

### 5.3.3 Heart Rate Variability during the Fine Motor and Visual Acuity Tasks

Heart rate variability is a factor that can be used to determine autonomic stress and recovery. By investigating short term HRV there can be an understanding on how certain conditions effect human dive comfort and in turn performance. This section expands on the effects of underwater conditions on heart rate variability.

HRV was investigated over changing light levels throughout the water turbidity conditions. This was to simulate changing light conditions while underwater. This was mostly to investigate if water and changing light conditions influenced HRV on humans underwater. There was no significant difference in any HRV factor (SDNN, RMSSD, pNN50, NN50, High frequency and Low frequency).

This is possibly due to the mammalian dive reflex that lowers HR while submerged in water (Schipke et al., 2001). This dive reflex to relax the sympathetic and parasympathetic nervous system, possibly as a means of conserving oxygen in unbreathable environments such as water to reduce the build-up of CO<sub>2</sub> in the body and keep the body alive long enough to return to a breathable environment. HRV is interesting as long-term measurements are usually taken (24hrs) to understand the physiological cycles of the body. Very little is known exactly about how HRV is impacted by water submersion. The test lengths were short so to increase the time the participants were exposed to the water conditions the HRV measurements were analysed between four and ten minutes. This allowed for all the fine motor test to be performed three times across each light level, thus simulating a change in light levels while working underwater. These results are similar to the results from a study conducted on 25 Scuba divers by Schipke and Pelzer in 2001, with some minor differences. Shipke and Pelzer's study found that there was no change to heart rate or HRV. This is similar to the study in this thesis where there was no significant change

to heart rate or HRV between water turbidity conditions or light conditions, however it is noted that a limitation of this thesis was no HRV or HR data was taken while participants were not submerged. An explanation for their findings was that when submerged, there is a mammalian dive reflex that induces bradycardia which may stabilise HRV in turn making the diver less susceptible to psychophysical stressors from the external environmental conditions.

There may also be an effect from the breathing apparatus on HRV as the participants were using SCUBA gear while submerged. This apparatus creates noise that may also impact how the participant copes with being underwater. Breathing compressed air while underwater has an impact on cognitive performance, and thus, there may also be an impact on HRV while breathing compressed air while submerged.

The most interesting finding of this investigation was that there was no significant difference in HRV or heart rate between conditions. HRV is a means to study and understand psychophysiological stress, and with the lack of significant results here it may be possible that there are other factors to identify and study.

More needs to be identified and understood in the effects of submersion, breathing modality and turbidity on HRV in humans.

#### 5.3.4 Interactional Effects of Turbidity and Lighting Conditions for performance and Heart Rate Variability

Interestingly, there were no interactional effects between either conditions on task performance or HRV. The findings of this study indicate that these factors impact human fine motor performance and visual acuity while operating underwater independently. This being said, future studies should aim to identify if any of these factors can interact with one another to impact human fine motor performance or visual acuity while operating underwater, as these interactions may be more complex than originally understood.

## **5.4 Qualitative Feedback and Researcher Observations of Participant Behaviour**

After each condition participants engaged in an informal conversation with the researcher to identify where they felt most comfortable in the hopes that these instances of comfortability or stress could then be linked to the results of the HRV analysis. While there were no differences in HRV between turbidity conditions or light conditions, this section expands on the conversation with participants on how they felt about each condition. In addition, the researcher recorded observations during each testing condition.

While there was no qualitative component to the methodology it was considered important to still report on the informal feedback participants provided during and after the different testing sessions.

### **5.4.1 Conditions and Tasks**

The condition in which the participants felt the most uncomfortable in was the moderate turbidity condition with low light. The condition which the participants felt the most comfortable in was the clear water condition with bright light. The participants reported that the fine motor task was the task they enjoyed the most, with some participants stating that they felt as if they had learned where each piece was meant to be put into the puzzle despite the puzzle being rotated between water turbidity conditions. Some participants dropped puzzle pieces while performing the test leading to longer performance times, this is still okay because to manipulate the puzzle pieces to and from the bag the participants had to use fine motor functions and proprioceptor feedback. More pieces were dropped during the clear water condition possibly due to some participants being unfamiliar with the pieces.

The task that participants struggled with the most was the visual acuity task, commenting on distortion of the Landolt-C rings that were displayed to them making their choice difficult.

Participants reported that there were particles in the water that would distract them when the light shined through the water onto them. These particles refracted light back

into their eyes possibly taking up some of their attention resource slightly reducing their ability to perform their task to the best of their ability.

The fine motor task could have been a little bit more difficult or more complicated to simulate real-world work that is done underwater. Participants reported that the task was relatively and didn't take much dexterity to complete. One participant said that the task could have been made more difficult with the addition of gloves. While this would reduce proprioceptor feedback the task is still relatively simple. The task could have also been suspended in the water allowing the participants to move and manipulate the puzzle in order to place the corresponding pieces into the puzzle. This was considered however if the puzzle was suspended then any piece of the puzzle could be placed into one slot, by laying the puzzle flat there was no way the puzzle could be completed if an error occurred. When speaking participants about this they reported that they almost placed wrong pieces into the wrong slot, if the puzzle was suspended then this could have occurred.

Participants reported that there was a minimal difference between the medium light condition and the low light condition in the presence of water turbidity. Low turbidity with low light levels did not feel different to low turbidity with medium light levels while underwater. The same statements were made for the moderate turbidity condition. While from observing outside the tank where testing was taking place there was a clear difference in light levels, however water does absorb some light naturally and this is increased with the presence of particles in the water. Participants reported seeing more particles in the water in the brightest light condition, this is due to the refraction of light bouncing off the particles in the water.

When asked how participants could make the conditions easier, they reported that increasing the light levels helped them and if the light levels could be increased more it may make the tasks even easier. In between each light condition there was a short period of time where the lights may have been turned off completely. In doing so the participant was submerged with a second or two with no light. When asked about that after the testing session participants reported that it was difficult to see and that made them feel uncomfortable. The worst of this was during the moderate turbidity condition where it felt as if they were in pitch black darkness. Participants said that if there was a testing condition with no light, they would not be able to see anything and would not

be able to perform the visual acuity test. However, the participants feel as if they could have done the shape puzzle, but it would have taken them a long time to do so.

#### 5.4.2 Underwater Experience

Participants that had underwater experience either through SCUBA, freediving or spear fishing said that the testing procedure was not an issue and that they were always comfortable in the water during testing, despite certain conditions like moderate turbidity being “eery” the experienced participants were at ease. Participants that had little experience underwater reported feeling more nervous and felt like they had to use more effort to complete the test procedures and breath through the SCUBA apparatus. Inexperienced participants may use more attention resources than experienced participants due to the novelty of what they were doing and that they were less accustomed to being submerged in the water. Participants that were comfortable underwater but had little experience with SCUBA reported the same, stating that they felt like they had to focus on breathing and completing the task whereas the participants who had SCUBA experience stated that they only had to focus on the task.

### 5.5 Implications

This study provides insight into the environments and work conducted underwater during dive operations. Divers are expected to perform a task while remaining safe. This involves all the sensory feedback that is available to an operator underwater. There is limited auditory feedback due to the noise of breathing apparatus and the sounds emitted from the environment and the communications from dive partners and dive supervisors above the surface. Proprioceptor feedback is limited due to partial pressure changes distally in the limbs when submerged with this feedback being reduced further with the need to use protective wear such as gloves on dive operations in colder water or for longer dive operations. This makes fine motor functioning difficult underwater as there is limited proprioceptor feedback from the hands and fingers when working on discrete tasks. This leaves visual feedback being the main source of environmental and task feedback for the dive operator. When diving in dark waters with limited natural light there is a need for artificial light sources to aid the diver. When

diving in turbid water a diver uses a dive light to help them complete a task or to check their dive gear to remain safe. Environmental conditions will change how a diver operates underwater, in turn affecting their performance.

## **Chapter 6 Conclusion**

### **6.1 Study Outcomes**

This study focused on the effects of light levels and turbidity on human fine motor performance and visual acuity performance underwater, where a fine motor task and Landolt-C visual acuity test were compared across three light levels; low, medium and bright light were compared with three turbidity levels; clear water, low turbidity and moderate turbidity. These conditions were chosen to simulate commercial diving conditions at various depths and different working areas underwater.

The main findings of this study were that visual acuity decreases as turbidity levels increase, and that increasing light levels will increase visual acuity regardless of the water turbidity level. While fine motor performance times increased significantly despite the increase in turbidity this shows that there was a learning effect present throughout the fine motor task testing. This shows that learning and experience will have a positive effect on fine motor performance even in increased turbidity conditions.

There was no interactional effect between light levels and water turbidity so in instances of increasingly turbid water a possible solution can be to increase light levels to improve both visual acuity and fine motor task performance.

### **6.2 Limitations**

There were a number of various factors that impacted the results and applicability of the research.

The population in which participants were recruited from was relatively small and the number of people within Makhanda and its surrounding areas that had diving experience and were willing to participate was even smaller. This meant that a compromise was made with the level of diving experience participants had to have in order to be included in the study. For the study dive experience was not necessary but rather participants were relatively comfortable underwater. This allowance of recruiting participants with no dive experience may have had confounding impacts on the results, particularly the HRV results.

While diver operators are expected to perform fine motor manipulations underwater, these tasks are more complicated than the task that was assessed. The task, while relatively simple was a common shape recognition puzzle similar to what is played with by children. This task may be familiar to everyone and easily learned. In real-world applications puzzle shapes are not used underwater except for in commercial diver training to assess fine motor function. The fine motor task was made relatively simple to allow for more participants to be recruited without the need for dive training and experience. Therefore, this task limits the real-world implications of this study.

Assessing vision underwater using Landolt-C rings does not accurately simulate real-world applications. Real-world dive operations and inspection tasks require the identification of multiple visual cues and various letters. The visual acuity test could have been more complex using various letters, shapes and colours to accurately simulate and study real-world implications when operating underwater.

The measure and analysis of HRV mostly compared the water condition's effects on the participants over short time periods. The time spent in the water under each light condition was not long enough to get relevant information on HRV. It may have been possible to lengthen each of the tests in order to prolong the time spent in the water under each light condition, whilst simultaneously lengthening the time spent in each water turbidity condition for a more applicable HRV analysis. An HRV baseline analysis was also not conducted as a measure to compare the water conditions and task performance to which limited the implications of the physiological assessments of task performance and comfortability in certain water conditions.

One of the largest limitations of this study was the inability to permute the water turbidity conditions. It was known from the beginning of the study that the water could not be drained between sessions in order to permute the turbidity conditions. Makhanda, where Rhodes University is situated is in a drought area. This meant that the hydrostatic tank where testing was conducted could not be drained and refilled between sessions, prohibiting permutation of turbidity. There is evidence of the learning effects between water conditions as turbidity increased between sessions two and four of testing. The effects of learning were attempted to be negated with the use of a familiar and simple task in the form of a shape puzzle board where participants practiced until their performance plateaued before their official testing sessions. It is

noted that the effects of learning still outweigh the effects of turbidity on fine motor performance. If turbidity conditions could be permuted the learning effects may be removed from the study altogether. Alternatively, if there was a way in which to test levels of turbidity looking through a tank into a turbid environment it can easily be permuted within the environmental context of Makhanda.

### **6.3 Recommendations**

The following recommendations are made considering future research into the effects of light levels and turbidity on human fine motor function, visual acuity and task performance.

- 1) A more complicated fine motor task to test how complex fine motor functions differ between light conditions and turbidity.
- 2) Test a fine motor task that is applicable to the real-world i.e. simulated welding or rigging of small bolts onto a larger assembly piece. This will be a more complex task that
- 3) Test baseline HRV measurements both on land and underwater. HRV is important in understanding the physiological effects of the task, however there must be a baseline that this can be compared to not just a comparison between water conditions while on task. This will give insight into how each task differs from the baseline, highlighting how each task may affect diver performance.
- 4) Recruitment of participants should be stricter, using only certified divers. Real-world underwater work is not conducted by inexperienced individuals therefore testing of this work should take the same considerations.
- 5) The visual acuity test needs to be more complex in order to simulate real-world applications, either by use of different letters or colours of letters and backgrounds. This will broaden the understanding of how underwater displays can be implemented in real-world scenarios to make dive operators tasks easier and reduce risks of errors.

- 6) Testing of visual acuity needs to be an accurately timed input from a participant (equipment permitting) underwater. Each response should be timed, allowing for a greater understanding on visual acuity per display. This will also allow for the timing under each light condition and not varied condition to further isolate the effects of light levels on visual acuity underwater.
- 7) Permutations of turbidity levels should be implemented to negate the effects of task learning effect.
- 8) Investigating the effects of no light can provide insight into how hazardous dive operators perform a task and how performance and safety could be improved.
- 9) Lastly, testing under turbidity can simulate real-world deep dives with the light source being attached to the diver, either on the head or arm. This will simulate real-world conditions and real-world implementations of equipment used to combat low light and turbid conditions.

#### **6.4 Future directions for diving**

The results of this study give insights into the effects of light levels and turbidity on human fine motor performance and visual acuity, as well as how learning can affect task performance. The results show that learning a simple fine motor task will improve performance regardless of water turbidity, light levels influence task performance. There was a significant improvement in task performance with the increase in light levels. However, the effect of turbidity needs to be studied in more depth. The current study offers a base for further research to be conducted. Applications of the findings of this study can be applied to further research isolating and investigating the effects of turbidity levels to a point of performance drop-off to understand how much turbidity a person can be exposed to where light will have no effect on performance.

Further possible research studies could investigate:

- 1) Visual acuity and fine motor performance looking through a glass tank, removing the effects of submersion on human task performance.

- 2) Fine motor performance and visual acuity in close to pitch black darkness with increasing light levels isolating the effect of light levels on task performance.
- 3) Task performance could be assessed comparing a well-lit area with a smaller light area to isolate distraction effects.

The knowledge and understanding of this research can provide insights and understanding into human task performance underwater and how this can be affected by light levels and water turbidity as well as experience. This can lead to safer working environments that are adapted to fit the human at any underwater work site, as well as improving the safety of underwater workspaces.

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# **Appendices**

## **Appendix A – General Information**

1. Letter of information to participants.
2. Participant consent form
3. Participant details
4. Permutation table
5. Ethical approval

## Appendix A1

Letter of information to participants

### INFORMATION TO PARTICIPANT

Rhodes University has given ethical clearance to this research project (***Ethics Approval Number: 2023-5747-7451***) and I have seen/may request to see the clearance certificate by contacting the Ethics Coordinator ([ethics-committee@ru.ac.za](mailto:ethics-committee@ru.ac.za))

Dear Participants,

Thank you for volunteering to participate in this master's research project. Your help and participation is greatly appreciated. This letter aims to inform you of the nature and proceedings of the master's research project titled:

#### **THE EFFECTS OF TURBIDITY AND LOW LIGHT ON HUMAN TASK PERFORMANCE AND VISUAL ACUITY UNDERWATER**

You should read this document carefully and thoroughly before signing the informed consent. If there are any questions about the study, please contact me (contact information at the end of the document).

#### **AIMS OF THE STUDY**

This study aims to assess the impact of working underwater (submersion) in low-light and turbid conditions. This study aims to establish the impact that the underwater environment and environmental demands have on task performance. By comparing the performance in low-light, medium-light and bright-light to performance in clear water, moderately turbid water and mostly turbid water in a controlled laboratory

environment underwater, an indication of the validity of laboratory-based testing results for underwater performance and visual acuity can be gained.

This study will be conducted underwater. During the three environmental conditions (clear water, moderately turbid water, and mostly turbid water), you will be required to complete a Landolt-C visual acuity test and a shape sorting puzzle.

## **TESTING SESSIONS**

There will be a total of four sessions in the study.

### **SESSION 1:**

The first session will be an information and habituation session in which you will be given all the relevant information relating to your involvement in the study. Once all the information has been given to you and your questions have been answered to your satisfaction, you will be given an informed consent form to read through and sign. After all the information has been given to you, all your questions have been answered, and you have signed the informed consent, the researcher will record your weight, indicated on a scale and height. Once your stature and mass have been recorded, you will have the opportunity to experience the underwater and on land setups.

### **SESSIONS 2 TO 4:**

Session 2 will consist of three tests and will take place in the clear water condition. Light exposure (bright, medium and low) will be permuted over the three tests.

Session 3 will consist of three tests and will take place in the moderately turbid water condition. Light exposure (bright, medium and low) will be permuted over the three tests.

Session 4 will consist of three tests and will take place in the mostly turbid water condition. Light exposure (bright, medium and low) will be permuted over the three tests.

You will complete the Landolt-C visual acuity test and shape sorting puzzle in different experimental light levels varying from low, medium, and bright light in each session.

All experimental conditions are performed underwater with assisted breathing (SCUBA cylinder and regulator) and a dive mask.

Please remember to bring a comfortable swimming costume, towel, and water bottle to all testing sessions. Please avoid caffeinated and/or alcoholic drinks for 12 hours before all conditions. Please avoid smoking for 3 hours prior to the testing. Please avoid eating a heavy meal immediately prior to the testing.

Table 1: Conditions (clear, moderate and mostly turbid water) for testing sessions in which light exposure (bright, medium and low) will be permuted.

		Water Conditions		
		Clear water	Low water turbidity	Moderate water turbidity
Light Conditions	Bright light	Session 2	Session 3	Session 4
	Medium light	Session 2	Session 3	Session 4
	Low light	Session 2	Session 3	Session 4

## RISKS

There are risks associated with this study, but these risks are not higher than the risks you would take during your normal underwater activities. The risks associated with underwater testing will be minimal. They will be conducted using assisted breathing close enough to the surface that exiting will require minimal effort (maximum depth of 2 meters). During all sessions, the researcher will be on hand to assist you in righting yourself and rapidly exiting to water should you feel you need to.

## BENEFITS

There are benefits that you may gain from this study. You will gain an understanding of how your information processing is affected by your submersion in water. This information may explain experiences you have had or felt when operating underwater.

Your participation will also contribute to a better understanding of the effects the changing of light levels and turbidity have on human task performance and visual acuity while operating underwater.

## **OTHER**

Your participation in this research is entirely voluntary, and you are free to withdraw from the testing if you feel unable or unwilling to complete the testing. All information collected during this study will be kept confidential, and codes will be used in place of any names. Photographs may be taken during testing as a demonstration of the testing procedure. All photographs taken of you will be edited, and all identifiable features will be blacked out. Also, the findings of this research may be referenced in future studies to explore this area thoroughly (Please refer to point 10 on the informed consent document).

Thank you in advance for your interest in this research. I have provided my contact details below. Should you have any questions, please feel free to contact me.

Yours sincerely:

Dane Smit (principal researcher)

(M.Sc. Student – Human Kinetics and Ergonomics department, Rhodes University)

[danesmit24@gmail.com](mailto:danesmit24@gmail.com) or 0726084910

## Appendix A2

Participant consent form

### **PARTICIPANT INFORMED CONSENT DECLARATION**

(To be signed by research participant/s)

Project Title: **THE EFFECTS OF TURBIDITY AND LIGHT LEVELS ON HUMAN TASK PERFORMANCE AND VISUAL ACUITY UNDERWATER**

**Dane Smit** from the Department of Human Kinetics and Ergonomics (HKE), Rhodes University Rhodes University has requested my permission to participate in the above-mentioned research project.

The nature and the purpose of the research project and of this informed consent declaration have been explained to me in a language that I understand.

I am aware that:

1. The purpose of the research project is to establish the impact of low light and turbidity on human task performance and visual acuity underwater.
2. Rhodes University has given ethical clearance to this research project (***Ethics Approval Number: 2023-5747-7451***) and I have seen/may request to see the clearance certificate by contacting the Ethics Coordinator ([ethics-committee@ru.ac.za](mailto:ethics-committee@ru.ac.za))
3. By participating in this research project, I will be contributing towards an understanding the impacts of underwater work on divers' task performance and vision, which may improve safety, work practices and training for underwater work.
4. I will participate in the project by completing four sessions and performing a landolt-c visual acuity test and a puzzle shape sorting task in each session. One session in clear water, one session in moderately turbid water and finally one last session in mostly turbid water. All sessions will have varied light levels from low, medium and bright light that will be permuted.
5. My participation is entirely voluntary and should I at any stage wish to withdraw from participating further, I may do so without any negative consequences.
6. The following risks are associated with my participation: I will be submerged in water for the duration of the testing; this poses the highest risk in the study. I will be using assisted breathing by means of SCUBA gear (cylinder and regulator) while submerged, reducing the risk. The underwater testing will take place in the HKE Department hydrostatic weighing tank, keeping the depth to less than 2 meters,

allowing me to push myself clear of the water level with ease. The Researcher is experienced with underwater research and will be on hand should I require any assistance while in the water. There is a slight risk of disorientation from the sensation of breathing underwater. However, this should pass in the habituation session, where I will have time to adjust to the sensation and become comfortable with it.

7. The Researcher intends to publish the research results in the form of a master's degree. However, confidentiality and anonymity of records will be maintained, and my name and identity will not be revealed to anyone who has not been involved in the conducting of the research, ***unless I indicate to the contrary/recognize that as a public figure my identity will inevitably be/become known, in which case I agree to accept the loss of anonymity.***
8. In terms of the Protection of Personal Information Act (No. 4 of 2013) it remains my right to request the Researcher to provide me with a detailed explanation of exactly how confidentiality and anonymity of the data I provide will be achieved. I may also request to know exactly how my personal information will be stored securely, for how long it will be stored.
9. If any data collected from me for this research project is to be used by the Researcher for any further study, I am to be informed in writing and my written consent requested again. I need not give consent for the new research if it is incompatible with the initial purpose of the present study (POPIA, s15(3)). Equally, I can simply reject the request. In such cases, a formal request needs to be made to me by the researcher via the Ethics Coordinator ([ethics-committee@ru.ac.za](mailto:ethics-committee@ru.ac.za)).
10. In terms of the POPI Act, I possess the right to receive feedback about this research. This will take the form of an email containing a report of the study's overall results, unless ***I elect not to receive this feedback.***
11. Any further questions that I might have regarding the nature of the research and/or my participation in it will be answered by Principal researcher, Dane Smit ([danesmit24@gmail.com](mailto:danesmit24@gmail.com)) or ([g17s1978@ru.ac.za](mailto:g17s1978@ru.ac.za)).
12. Any complaints or statements that I might have regarding the nature of the research and/or my participation in it can be sent to the principal researchers supervisor, Dr. Swantje Wells ([s.wells@ru.ac.za](mailto:s.wells@ru.ac.za)) or the ethics coordinator, ([ethics-committee@ru.ac.za](mailto:ethics-committee@ru.ac.za))
13. By signing this informed consent declaration, I am not waiving any legal claims, rights, or remedies. A copy of this informed consent declaration will be given to me, and the original will be kept on record by the Researcher.
14. I ***agree/disagree*** (delete inapplicable) to the Researcher's request to take photographs, or videoing me as part of this research project, recognizing that agreement here is likely to raise the risk of compromising my anonymity and that steps will be taken to ensure this will not happen if my consent is given.

I, ....., have read the above information / confirm that the above information has been explained to me in a language that I understand, and I am aware of this document's contents. I have asked all the questions that I wished to ask, and these have been answered to my satisfaction. I fully understand what is expected of me during the research.

I have not been pressurised in any way and I voluntarily agree to participate in the above-mentioned project.

.....  
**Participants signature**

.....  
**Witness**

.....  
**Date**

## Appendix A3

### Participant details

Table A1: Participant characteristics

Participant Code	No .	Experience	Gender	Age	Weight (kg)	Height (mm)
P001	1	YES	M	24	88,8	1800
P002	2	NO	F	23	62,8	1655
P003	3	YES	M	26	92,2	1780
P004	4	YES	M	30	73,9	1680
P005	5	YES	M	24	104,2	1875
P006	6	YES	F	21	64,1	1710
P007	7	NO	M	21	90,4	1855
P008	8	NO	M	21	75	1845
P009	9	NO	F	20	64,8	1665
P010	10	YES	M	35	95	1800
P011	11	YES	M	27	111,8	1775
P012	12	NO	M	20	59,8	1775
P013	13	NO	F	23	94	1642
P014	14	NO	M	21	57,4	1720
P015	15	YES	F	23	59,5	1650
P016	16	NO	F	23	101,6	1720
P017	17	YES	M	25	70,1	1750
P018	18	YES	M	23	69,2	1770

## Appendix A4

### Permutation table

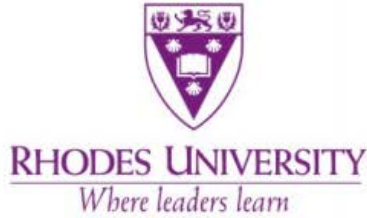
Table A2: Light permutation table for testing sessions

Participant	No.	LIGHT PERMUTATION								
		Clear water			Low turbidity			Moderate turbidity		
LIGHT CONDITION ORDER		1	2	3	1	2	3	1	2	3
P001	1	L	M	B	L	M	B	L	M	B
P002	2	L	B	M	L	B	M	L	B	M
P003	3	M	B	L	M	B	L	M	B	L
P004	4	M	L	B	M	L	B	M	L	B
P005	5	B	M	L	B	M	L	B	M	L
P006	6	B	L	M	B	L	M	B	L	M
P007	7	L	M	B	L	M	B	L	M	B
P008	8	L	B	M	L	B	M	L	B	M
P009	9	M	B	L	M	B	L	M	B	L
P010	10	M	L	B	M	L	B	M	L	B
P011	11	B	M	L	B	M	L	B	M	L
P012	12	B	L	M	B	L	M	B	L	M
P013	13	L	M	B	L	M	B	L	M	B
P014	14	L	B	M	L	B	M	L	B	M
P015	15	M	B	L	M	B	L	M	B	L
P016	16	M	L	B	M	L	B	M	L	B
P017	17	B	M	L	B	M	L	B	M	L
P018	18	B	L	M	B	L	M	B	L	M

KEY	
<b>B</b>	Bright
<b>M</b>	Medium
<b>L</b>	Low

# Appendix A5

## Ethical approval



**Rhodes University Human Research Ethics Committee**  
PO Box 94, Makhanda, 6140, South Africa  
t: +27 (0) 46 603 7727  
f: +27 (0) 46 603 8822  
e: [ethics-committee@ru.ac.za](mailto:ethics-committee@ru.ac.za)

<https://www.ru.ac.za/researchgateway/ethics/>

20 April 2023

Dane SMIT

Email: [g17s1978@campus.ru.ac.za](mailto:g17s1978@campus.ru.ac.za) [danesmit24@gmail.com](mailto:danesmit24@gmail.com)

Review Reference: 2023-5747-7451

Dear Dane SMIT

**Title:** The effects of turbidity and low-light on human performance and visual acuity under water

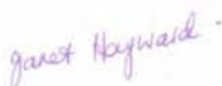
Researcher: Dane SMIT

This letter confirms that the above research proposal has been reviewed and **APPROVED** by the Rhodes University Human Research Ethics Committee (RU-HREC). Your Approval number is: 2023-5747-7451

Approval has been granted for 1 year. An annual progress report will be required in order to renew approval for an additional period. You will receive an email notifying you when the annual report is due.

Please ensure that the ethical standards committee is notified should any substantive change(s) be made, for whatever reason, during the research process. This includes changes in investigators. Please also ensure that a brief report is submitted to the ethics committee on the completion of the research. The purpose of this report is to indicate whether the research was conducted successfully, if any aspects could not be completed, or if any problems arose that the ethical standards committee should be aware of. If a thesis or dissertation arising from this research is submitted to the library's electronic theses and dissertations (ETD) repository, please notify the committee of the date of submission and/or any reference or cataloguing number allocated.

Sincerely,



**Dr Janet Hayward**

**Chair: Rhodes University Human Research Ethics Committee, RU-HREC**

cc: Ethics Coordinator

## **Appendix B – Task performance Statistics Work in RStudio**

1. Fine motor performance
2. Visual acuity performance

## Appendix B1

Fine motor task

```
> `FMT` <- read.csv("FMT.csv")
> FMT$turbidity <- factor(FMT$turbidity, levels = c("1", "2", "3"), labels = c("Clear",
"Low", "Moderate"))
> FMT$light <- factor(FMT$light, levels = c("1", "2", "3"), labels = c("Bright",
"Medium", "Low"))
> FMT$participant <- as.factor(FMT$participant)
> FMT$MEASURE <- as.numeric(FMT$time)
> shapiro.test(FMT$time)
```

Shapiro-Wilk normality test

data: FMT\$time

W = 0.95719, p-value = 7.081e-05

```
> model_FMT <- art(time ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(time)

	F	Df	Df.res	Pr(>F)
1 turbidity	6.95097	2	136	0.00133584 **
2 light	7.34348	2	136	0.00093648 ***
3 turbidity:light	0.41702	4	136	0.79614641

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	22.07	6.39	136	3.454	0.0021
Clear - Moderate	18.81	6.39	136	2.944	0.0106
Low - Moderate	-3.26	6.39	136	-0.510	0.8666

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	-6.83	6.47	136	-1.056	0.5428
Bright - Low	-24.06	6.47	136	-3.719	0.0008
Medium - Low	-17.22	6.47	136	-2.662	0.0235

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$RR)
```

```
> shapiro.test(FMT$RR)
```

Shapiro-Wilk normality test

data: FMT\$RR

W = 0.9522, p-value = 2.492e-05

```
> model_FMT <- art(RR ~ turbidity * light + (1|participant), data = FMT)
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(RR)

	F	Df	Df.res	Pr(>F)
1 turbidity	3.74193	2	136	0.026184 *
2 light	0.20784	2	136	0.812593
3 turbidity:light	0.61301	4	136	0.653976

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	-6.57	5.81	136	-1.132	0.4962
Clear - Moderate	-15.81	5.81	136	-2.723	0.0199
Low - Moderate	-9.24	5.81	136	-1.591	0.2530

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
----------	----------	----	----	---------	---------

```
Bright - Medium    3.70 5.87 136  0.631 0.8032
Bright - Low       2.52 5.87 136  0.429 0.9035
Medium - Low      -1.19 5.87 136 -0.202 0.9778
```

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$SDNN)
```

```
> shapiro.test(FMT$SDNN)
```

Shapiro-Wilk normality test

```
data: FMT$SDNN
```

```
W = 0.77269, p-value = 1.421e-14
```

```
> model_FMT <- art(SDNN ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(SDNN)

	F	Df	Df.res	Pr(>F)
1 turbidity	2.0917	2	136	0.12743
2 light	1.5415	2	136	0.21777
3 turbidity:light	0.7264	4	136	0.57537

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	10.20	6.68	136	1.528	0.2810
Clear - Moderate	-2.76	6.68	136	-0.413	0.9102
Low - Moderate	-12.96	6.68	136	-1.941	0.1311

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	9.833	6.62	136	1.486	0.3008
Bright - Low	-0.444	6.62	136	-0.067	0.9975
Medium - Low	-10.278	6.62	136	-1.553	0.2697

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$HR)
```

```
> shapiro.test(FMT$HR)
```

Shapiro-Wilk normality test

data: FMT\$HR

W = 0.98331, p-value = 0.04827

```
> model_FMT <- art(HR ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(HR)

	F	Df	Df.res	Pr(>F)
1 turbidity	3.72024	2	136	0.026728 *
2 light	0.17172	2	136	0.842394
3 turbidity:light	0.63963	4	136	0.635119

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	6.46	5.79	136	1.117	0.5054
Clear - Moderate	15.70	5.79	136	2.714	0.0204
Low - Moderate	9.24	5.79	136	1.597	0.2505

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	-3.43	5.85	136	-0.585	0.8282
Bright - Low	-1.57	5.85	136	-0.269	0.9609

Medium - Low      1.85 5.85 136   0.316 0.9463

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$RMSSD)
```

```
> shapiro.test(FMT$RMSSD)
```

Shapiro-Wilk normality test

data: FMT\$RMSSD

W = 0.74061, p-value = 1.33e-15

```
> model_FMT <- art(RMSSD ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(RMSSD)

	F	Df	Df.res	Pr(>F)
1 turbidity	1.86993	2	136	0.15808
2 light	0.55454	2	136	0.57563
3 turbidity:light	0.62992	4	136	0.64197

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	8.13	6.65	136	1.222	0.4424
Clear - Moderate	-4.57	6.65	136	-0.687	0.7712
Low - Moderate	-12.70	6.65	136	-1.909	0.1400

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	6.33	6.69	136	0.947	0.6115
Bright - Low	0.50	6.69	136	0.075	0.9969
Medium - Low	-5.83	6.69	136	-0.872	0.6586

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$pNN50)
```

```
> shapiro.test(FMT$pNN50)
```

Shapiro-Wilk normality test

```
data: FMT$pNN50
```

```
W = 0.8871, p-value = 9.13e-10
```

```
> model_FMT <- art(pNN50 ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(pNN50)

	F	Df	Df.res	Pr(>F)
1 turbidity	0.44697	2	136	0.64050
2 light	1.31482	2	136	0.27191
3 turbidity:light	0.10947	4	136	0.97904

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	2.81	5.49	136	0.513	0.8653
Clear - Moderate	-2.37	5.49	136	-0.432	0.9025
Low - Moderate	-5.19	5.49	136	-0.944	0.6133

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	8.69	5.53	136	1.571	0.2615
Bright - Low	2.43	5.53	136	0.439	0.8993
Medium - Low	-6.26	5.53	136	-1.132	0.4958

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$LF)
```

```
> shapiro.test(FMT$LF)
```

Shapiro-Wilk normality test

data: FMT\$LF

W = 0.95864, p-value = 9.7e-05

```
> model_FMT <- art(LF ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(LF)

	F	Df	Df.res	Pr(>F)
1 turbidity	0.15072	2	136	0.86023
2 light	1.34785	2	136	0.26325
3 turbidity:light	0.41322	4	136	0.79889

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	3.833	8.43	136	0.454	0.8925

```
Clear - Moderate -0.333 8.43 136 -0.040 0.9991
Low - Moderate -4.167 8.43 136 -0.494 0.8743
```

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	11.722	8.36	136	1.402	0.3430
Bright - Low	-0.333	8.36	136	-0.040	0.9991
Medium - Low	-12.056	8.36	136	-1.441	0.3227

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$HF)
```

```
> shapiro.test(FMT$HF)
```

Shapiro-Wilk normality test

data: FMT\$HF

W = 0.95859, p-value = 9.586e-05

```
> model_FMT <- art(HF ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(HF)

	F	Df	Df.res	Pr(>F)
1 turbidity	0.15086	2	136	0.86011
2 light	1.32426	2	136	0.26941
3 turbidity:light	0.40656	4	136	0.80368

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	-3.833	8.43	136	-0.455	0.8924
Clear - Moderate	0.333	8.43	136	0.040	0.9991
Low - Moderate	4.167	8.43	136	0.494	0.8742

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	-11.556	8.36	136	-1.382	0.3531
Bright - Low	0.444	8.36	136	0.053	0.9984
Medium - Low	12.000	8.36	136	1.435	0.3258

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> FMT$MEASURE <- as.numeric(FMT$LF_HF)
```

```
> shapiro.test(FMT$LF_HF)
```

Shapiro-Wilk normality test

```
data: FMT$LF_HF
```

```
W = 0.66869, p-value < 2.2e-16
```

```
> model_FMT <- art(LF_HF ~ turbidity * light + (1|participant), data = FMT)
```

```
> anova(model_FMT)
```

Analysis of Variance of Aligned Rank Transformed Data

Table Type: Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Model: Mixed Effects (lmer)

Response: art(LF\_HF)

	F	Df	Df.res	Pr(>F)
1 turbidity	0.19870	2	136	0.82004
2 light	1.73322	2	136	0.18060
3 turbidity:light	0.58269	4	136	0.67569

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

```
> posthoc_turbidity <- art.con(model_FMT, "turbidity")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_turbidity)
```

contrast	estimate	SE	df	t.ratio	p.value
Clear - Low	5.11	8.34	136	0.613	0.8132
Clear - Moderate	1.50	8.34	136	0.180	0.9823
Low - Moderate	-3.61	8.34	136	-0.433	0.9018

Results are averaged over the levels of: light

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

```
> posthoc_light <- art.con(model_FMT, "light")
```

NOTE: Results may be misleading due to involvement in interactions

```
> summary(posthoc_light)
```

contrast	estimate	SE	df	t.ratio	p.value
Bright - Medium	9.83	8.16	136	1.205	0.4522
Bright - Low	-5.11	8.16	136	-0.626	0.8059
Medium - Low	-14.94	8.16	136	-1.832	0.1632

Results are averaged over the levels of: turbidity

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 3 estimates

## Appendix B2

Visual acuity task

```
> VA <- read.csv("VAPT.csv")
> VA$turbidity <- factor(VA$turbidity, levels = c("1", "2", "3"), labels = c("Clear",
"Low", "Moderate"))
> VA$participant <- as.factor(VA$participant)
> VA$time <- as.numeric(VA$time)
> shapiro.test(VA$time)
```

Shapiro-Wilk normality test

data: VA\$time

W = 0.87408, p-value = 4.061e-05

```
> friedman_result <- friedman_test(data = VA, formula = time ~ turbidity | participant)
> print(friedman_result)
```

# A tibble: 1 × 6

```
.y.    n statistic  df    p method
* <chr> <int>  <dbl> <dbl> <dbl> <chr>
1 time   18   18.1    2 0.000117 Friedman test
```

```
> pairwise_result <- VA %>% pairwise_wilcox_test(time ~ turbidity, paired = TRUE,
p.adjust.method = "holm")
```

```
> print(pairwise_result)
```

# A tibble: 3 × 9

```
.y. group1 group2  n1  n2 statistic    p  p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int>  <dbl>  <dbl>  <dbl> <chr>
1 time Clear Low      18  18   167 0.000419 0.000838 ***
2 time Clear Moderate 18  18   162 0.000252 0.000756 ***
3 time Low  Moderate 18  18   123 0.107    0.107    ns
```

```
> shapiro.test(VA$correct)
```

### Shapiro-Wilk normality test

data: VA\$correct

W = 0.69173, p-value = 2.331e-09

```
> friedman_result <- friedman_test(data = VA, formula = correct ~ turbidity |  
participant)
```

```
> print(friedman_result)
```

```
# A tibble: 1 × 6
```

```
  .y.      n statistic  df      p method  
* <chr> <int> <dbl> <dbl> <dbl> <chr>  
1 correct  18  25.1  2 0.00000348 Friedman test
```

```
> pairwise_result <- VA %>% pairwise_wilcox_test(correct ~ turbidity, paired =  
TRUE, p.adjust.method = "holm")
```

```
> print(pairwise_result)
```

```
# A tibble: 3 × 9
```

```
  .y. group1 group2  n1  n2 statistic    p  p.adj p.adj.signif  
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>  
1 correct Clear Low 18 18 120 0.000659 0.001 **  
2 correct Clear Moderate 18 18 153 0.000306 0.000918 ***  
3 correct Low Moderate 18 18 105 0.059 0.059 ns
```

```
> shapiro.test(VA$SDNN)
```

### Shapiro-Wilk normality test

data: VA\$SDNN

W = 0.82135, p-value = 1.366e-06

```
> friedman_result <- friedman_test(data = VA, formula = SDNN ~ turbidity |  
participant)
```

```

> print(friedman_result)
# A tibble: 1 × 6
  .y.    n statistic  df    p method
* <chr> <int>  <dbl> <dbl> <dbl> <chr>
1 SDNN   18    1.44    2 0.486 Friedman test
> pairwise_result <- VA %>% pairwise_wilcox_test(SDNN ~ turbidity, paired =
TRUE, p.adjust.method = "holm")
> print(pairwise_result)
# A tibble: 3 × 9
  .y. group1 group2  n1  n2 statistic  p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 SDNN Clear Low      18  18    117 0.181 0.543 ns
2 SDNN Clear Moderate  18  18     85 1    1 ns
3 SDNN Low Moderate  18  18     66 0.417 0.834 ns
> shapiro.test(VA$pnnXX)

```

#### Shapiro-Wilk normality test

```

data: VA$pnnXX
W = 0.89898, p-value = 0.0002614

```

```

>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = pnnXX ~ turbidity |
participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6
  .y.    n statistic  df    p method
* <chr> <int>  <dbl> <dbl> <dbl> <chr>

```

```

1 pnnXX 18 0.197 2 0.906 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(pnnXX ~ turbidity, paired =
TRUE, p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
  .y. group1 group2  n1  n2 statistic  p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 pnnXX Clear Low 18 18 90 0.865 1 ns
2 pnnXX Clear Moderate 18 18 74 0.925 1 ns
3 pnnXX Low Moderate 18 18 72 0.58 1 ns
> shapiro.test(VA$RMSSD)

```

#### Shapiro-Wilk normality test

```

data: VA$RMSSD
W = 0.7999, p-value = 4.049e-07
>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = RMSSD ~ turbidity |
participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6
  .y. n statistic df p method

```

```

* <chr> <int> <dbl> <dbl> <dbl> <chr>
1 RMSSD 18 1.33 2 0.513 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(RMSSD ~ turbidity, paired =
TRUE, p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
 .y. group1 group2 n1 n2 statistic p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 RMSSD Clear Low 18 18 115 0.212 0.636 ns
2 RMSSD Clear Moderate 18 18 87 0.966 0.966 ns
3 RMSSD Low Moderate 18 18 65 0.393 0.786 ns
> shapiro.test(VA$HR)

```

#### Shapiro-Wilk normality test

data: VA\$HR

W = 0.96958, p-value = 0.1847

```

>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = HR ~ turbidity | participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6
 .y. n statistic df p method

```

```

* <chr> <int> <dbl> <dbl> <dbl> <chr>
1 HR 18 1.33 2 0.513 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(HR ~ turbidity, paired = TRUE,
p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
 .y. group1 group2 n1 n2 statistic p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 HR Clear Low 18 18 66 0.417 0.834 ns
2 HR Clear Moderate 18 18 95 0.702 0.834 ns
3 HR Low Moderate 18 18 113 0.246 0.738 ns
> shapiro.test(VA$RR)

```

#### Shapiro-Wilk normality test

```

data: VA$RR
W = 0.96974, p-value = 0.1878
>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = RR ~ turbidity | participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6
 .y. n statistic df p method

```

```

* <chr> <int> <dbl> <dbl> <dbl> <chr>
1 RR 18 1.33 2 0.513 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(RR ~ turbidity, paired = TRUE,
p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
 .y. group1 group2 n1 n2 statistic p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 RR Clear Low 18 18 103 0.468 1 ns
2 RR Clear Moderate 18 18 75 0.671 1 ns
3 RR Low Moderate 18 18 63 0.347 1 ns
> shapiro.test(VA$LF)

```

#### Shapiro-Wilk normality test

```

data: VA$LF
W = 0.95847, p-value = 0.05884
>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = LF ~ turbidity | participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6
 .y. n statistic df p method

```

```

* <chr> <int> <dbl> <dbl> <dbl> <chr>
1 LF 18 0.778 2 0.678 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(LF ~ turbidity, paired = TRUE,
p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
 .y. group1 group2 n1 n2 statistic p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 LF Clear Low 18 18 112 0.265 0.795 ns
2 LF Clear Moderate 18 18 89 0.899 1 ns
3 LF Low Moderate 18 18 75 0.671 1 ns
> shapiro.test(VA$HF)

```

#### Shapiro-Wilk normality test

```

data: VA$HF
W = 0.95838, p-value = 0.05833
>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = HF ~ turbidity | participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6
 .y. n statistic df p method

```

```

* <chr> <int> <dbl> <dbl> <dbl> <chr>
1 HF 18 0.778 2 0.678 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(HF ~ turbidity, paired = TRUE,
p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
 .y. group1 group2 n1 n2 statistic p p.adj p.adj.signif
* <chr> <chr> <chr> <int> <int> <dbl> <dbl> <dbl> <chr>
1 HF Clear Low 18 18 58 0.246 0.738 ns
2 HF Clear Moderate 18 18 83 0.932 1 ns
3 HF Low Moderate 18 18 96 0.671 1 ns
> shapiro.test(VA$LF_HF)

```

#### Shapiro-Wilk normality test

```

data: VA$LF_HF
W = 0.85257, p-value = 9.407e-06
>
> # Run Friedman test
> friedman_result <- friedman_test(data = VA, formula = LF_HF ~ turbidity |
participant)
>
> #view the results of the friedman test
> print(friedman_result)
# A tibble: 1 × 6

```

```

.y.    n statistic  df  p method
* <chr> <int>    <dbl> <dbl> <dbl> <chr>
1 LF_HF  18    0.778   2 0.678 Friedman test
>
> # Post-hoc pairwise Wilcoxon signed-rank tests with Holm adjustment, if the
friendman test is significant
> pairwise_result <- VA %>% pairwise_wilcox_test(LF_HF ~ turbidity, paired =
TRUE, p.adjust.method = "holm")
>
> # Print the results of the post-hoc test
> print(pairwise_result)
# A tibble: 3 × 9
.y.  group1 group2  n1  n2 statistic  p p.adj p.adj.signif
* <chr> <chr> <chr>  <int> <int>  <dbl> <dbl> <dbl> <chr>
1 LF_HF Clear  Low    18  18    109 0.325 0.975 ns
2 LF_HF Clear  Moderate 18  18    76 0.702 1  ns
3 LF_HF Low    Moderate 18  18    74 0.64 1  ns

```