Progression in cognitive-affective research by increasing ecological validity: A series of Virtual Reality studies.

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“*The most important step a [hu]man can take.*

It's not the first one, is it?

It's the next one.

Always the next step”

— Brandon Sanderson, Oathbringer (2017)

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0. General Abstract

The ultimate aim of psychological research is to disentangle everyday human functioning. Achieving this goal has always been limited by the necessity of balancing experimental control and ecological validity. Recent technical advances, however, reduce this trade-off immensely, perhaps even rendering it void: Sophisticated virtual reality (VR) systems provide not only high experimental control but also multidimensional and realistic stimuli, tasks, and experimental setups. Yet prior to applying VR as a standalone experimental method, an empirical foundation for its application needs to be established.

To this end, this dissertation aims to shed light on whether and which changes in cognitive-affective standard findings result from increasing the ecological validity by means of VR paradigms. The four empirical studies included in this dissertation focus either on the affective or mnemonic processes and mechanisms occurring under immersive VR conditions compared to conventional laboratory setups. Study 1.1 investigated whether the electrophysiological correlates of the approach/avoidance dimension differ depending on the mode of presentation, i.e., immersive VR footage or a virtual 2D desktop. Study 2 was extended by a behavioral component. Full-body responses were enabled within this paradigm to examine holistic fear responses and to put to the test whether the respective electrophysiological responses translate from keystrokes to natural responses. With respect to the retrieval of such immersive experiences, Study 1.2 aimed to replicate the memory superiority effect found for VR conditions compared to conventional conditions. The generalizability of this effect will be examined using complex, multimodal scenes. Going one step further, Study 3 differentiated the retrieval mechanisms underlying VR-based or conventional laboratory engrams on the electrophysiological level. The well-established theta old/new effect served as a benchmark to check whether cognitive processes obtained under conventional conditions translate to VR conditions.

The results of these studies are discussed with respect to whether and how increasing ecological validity alters the standard findings expected on the basis of the previous research background. Special attention will be paid to the differences between conventional laboratory setups and sophisticated VR setups with the aim to identify possible sources of the obtained deviations from standard findings. Such changes in the findings that overlap and exceed all studies beyond their primary focus, whether

emotional or mnemonic, are discussed in terms of embodied simulations and the predictive coding hypothesis. A shared mental 3D default space is proposed as a possible source of fundamental differences between conventional and VR-based research outcomes. In particular, it will be demonstrated that conventional research approaches and findings may not only be amplified but fundamentally altered when translated to VR paradigms.

1. Introduction

1.1 Virtual Wonderland

The tale of Alice in Wonderland[1] seems wonderous, fabulous, spectacular - and absolutely, indisputably impossible. Stepping through a rabbit's hole and tumbling into another world is something a healthy human mind would insist on being unbelievable nonsense. At least this holds true for the past centuries. Today, however, we need to question this assumption of absolute impossibility. Putting on a virtual reality (VR) head-mounted display (HMD) and exploring virtual worlds would not sound any saner to the minds of 1865 than jumping through a rabbit's hole. However, the former has become a common experience for tech geeks, and is increasingly finding its way into business, education and even peoples' everyday lives (e.g., Slater & Sanchez-Vives, 2016; Suh & Prophet, 2018). Similarly, VR attracts the interest of researchers of the most different fields. In recent years, not only VR as a research objective in its own right but also the opportunity to use this technology as a tool for, among others, psychological research has moved straight into the scientific community's focus (e.g., Parsons, 2015; Slater & Sanchez-Vives, 2016). Strictly speaking, VR is not an entirely new idea – e.g., virtual reality exposure therapy (VRET) was applied as early as in the 90s (Hodges et al., 1994). However, since 2016 technical advances led to a boom in VR research (see Cipresso et al., 2018). Google scholar lists more than 96,500 publications published between 2016 and today[2] that titles contain "virtual reality". Why would a fancy screen mounted to the forehead attract the attention of so many?

The overall reason why VR gained more and more popularity in psychological research, and at the same time one of the greatest benefits of VR as an experimental tool, is its ability to submerse the user into complex and multidimensional but likewise controlled environments (Parsons, 2015). At the most basic level, the ultimate aim of psychological research is to understand the processes and mechanisms underlying human experiences and behavior in everyday life (de la Rosa & Breidt, 2018).

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[1] Lewis Carroll's novel „Alice's Adventures in Wonderland" (1865) tells the tale of a young girl entering a subterranean fantasy world through a rabbit hole. In this world, Alice encounters the most fantastic creatures and phenomena, paradoxes and absurdities (Carroll, 1865).

[2] Retrieved on 2021-08-24 via Google Scholar search, key word "virtual reality" for the period 2016 to 2021, excluding quotes.

Since its early days, most of this research process has been based on highly controlled and abstract conditions in the laboratory, cut off from their original context (Nastase et al., 2020). For example, the retrieval of learned word lists (e.g., Tulving & Psotka, 1971) is supposed to reveal the functioning of everyday memory. However, such abstract tasks stand in stark contrast to the real-life equivalent they are supposed to mirror. They fall short of capturing reality in a holistic way, considering that the results are applicable to only few real-world situations, e.g., memorizing a shopping list. The balancing act between high control and high realism of experimental settings has always been present in psychological research - sometimes more, sometimes less prominent (Kvavilashvili & Ellis, 2004) as will be illustrated in more detail in chapter 1.2. However, VR experiences might pick up the pieces and assemble the puzzle: Why settle for having participants learn and recall a - possibly trivial - word list when you can have them perform the overall task - e.g., grocery shopping - under highly realistic but equally controlled conditions using VR applications (e.g., Alderman et al., 2003)? The immersive, multimodal nature of VR experiences offers the opportunity to immensely increase the realism and naturalness of psychological experiments without impacting experimental control (e.g., Parsons, 2015; Parsons et al., 2020; Smith, 2019).

Nevertheless, prior to using current VR technology as an experimental tool, an empirical foundation for its application needs to be obtained. It needs to be clarified to what extend findings from VR settings are comparable to results from corresponding standard paradigms which have been frequently replicated in conventional laboratory experiments. Accordingly, this dissertation focuses on the examination of differences between outcomes obtained from immersive VR settings and from conventional laboratory settings. In four empirical studies, well-established cognitive-affective processes and mechanisms that have been broadly studied in conventional settings are used for comparison. To this end, psychological standard paradigms will on the one hand be replicated by use of conventional methods, providing the current research state's foundation. On the other hand, they will be translated to immersive VR settings to put to the test to what extent findings obtained from VR setups differ. Moreover, VR environments will be varied in several design parameters to determine their effect on the research outcome. In Study 1.1 and Study 2, the electrophysiological correlates of affective processing are recorded during the presentation of the stimulus material, providing insights into the immediate emotional-motivational tendencies exhibited during either VR experiences or conventional laboratory ones. Study 1.2 and Study 3 will focus on the retrieval of both kinds of experience by assessment of memory performance (both studies) and the electrophysiological correlates of a canonical memory task (Study 3).

The general discussion will focus on respective differences emerging between said VR experiences and conventional ones. The intersections between the studies dedicated to affective outcomes, as well as those between the studies dedicated to cognitive outcomes, will first be considered and integrated. Changes in cognitive-affective processes and mechanisms consistent across studies are integrated with respect to the underlying VR characteristics and the differences between the two experimental approaches. The focus is on VR's ability to provide realistic, multisensory input to the sensory channels and thus to facilitate more natural processing compared to conventional stimuli. Therefore, VR experiences might be integrated into the default mode network by means of a mental 3D default space. Ethical limits concerning VR's application relevant to the respective studies are highlighted and the overarching findings of the discussion are summarized.

In other words, if someone follows Alice down the rabbit hole and feels as if they were actually there, their overall emotional response might correspond to their real-world response (Study 1.1, 2). Equally integral might be whether and how this experience is remembered and integrated into existing memories. If the virtual experience would be remembered alike everyday memories (Study 1.2, 3), the experience might profoundly and permanently affect future experiences and behaviors - even those that do not take place in the rabbit hole but the real world - therefore not constituting a whole new field of research in itself but offering advancement and refinement of the existing cognitive-affective research.

1.2 The real-life/laboratory controversy

The inverse relationship between high experimental control and high naturalness in psychological research (Kvavilashvili & Ellis, 2004) has long been handled by according supremacy to experimental control: The experimental tasks and environments were designed so systematically that any influence on the variable under study could be controlled as effectively as possible. This procedure aimed to isolate the phenomenon under investigation from unintended influences and to exclude alternative explanations of the research outcome (Nastase et al., 2020; Shamay-Tsoory & Mendelsohn, 2019). This way, researchers aimed to identify general rules and principles which would transfer to everyday life (Nastase et al., 2020).

It took some time before the extent to which models derived from said sterile conditions reflect everyday human functioning was questioned. Criticism was raised that the nature of the studied phenomena would not be correctly predicted if they were completely isolated from their co-processes and the context in which they usually occur. For example, Neisser[3] (Neisser, 1976, 1985) challenged the traditional laboratory approach by expressing that its scientific progress, particularly in memory research, broadly relied on artificial settings and tasks hardly resembling everyday contexts and affordances. To this end, ecological validity was proposed as a counterweight of experimental control (Kvavilashvili & Ellis, 2004).

In short, ecological validity refers to the match between an experiment and its real-life counterparts (Parsons, 2015; Shamay-Tsoory & Mendelsohn, 2019). Originally, the term was introduced by Egon Brunswik (1955) to quantify the informative value of sensory cues in perceptual processes (see also Kihlstrom, 2021). In Brunswik's understanding, ecological validity refers to the degree to which a cue correlates with and thus predicts a property of a real-world object or occurrence, serving probabilistic functions. As outlined in his lens model, the distal cues used in an experiment are not perceived unfiltered but through a "lens", rendering the proximal cues imperfect. Hence, it would be the researcher's highest aim to minimize the lenses’ dispersion and to create an accurate perception of real-world cues in the experimental context (Brunswik, 1955).

The more widespread notion of ecological validity as the match between the experiment and its real-life counterpart was based on Orne's (1962) re-interpretation that experiments lack ecological validity if they contain characteristics that are unique to the experimental setting but without equivalent in real-world environments (see also Kihlstrom, 2021). In the light of this definition, classical laboratory studies seemed rather artificial, corresponding to few real-life counterparts (Nastase et al., 2020). This criticism triggered an ongoing exchange of blows between proponents of the ecological and the

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[3] Neisser is considered one of the leading proponents of the ecological approach. Yet he was neither the first nor the only one criticizing traditional, sterile laboratory conditions (see e.g., Kvavilashvili & Ellis, 2004).

traditional approaches, as both claimed to achieve superior generalizability compared to the other (Banaji & Crowder, 1989, 1991). The most compelling argument from the traditional approach's perspective seemed to be that certain phenomena would not be amenable to study without high experimental control because too many confounds occurred in naturalistic settings (Banaji & Crowder, 1989, 1991). Vice versa, the ecological approach's proponents argued that findings from sterile laboratories would not transfer to naturalistic and rich settings (Nastase et al., 2020; Neisser, 1985; Shamay-Tsoory & Mendelsohn, 2019). Thus, what the traditional approach sought to exclude as confounding variables, the ecological approach considered as possibly relevant subcomponents within the larger entity. Yet it was completely lost in the stereotype debate that both sides drew the bottom line that both experimental control and ecological validity should be maintained at high levels. Only in those cases where only one of the two factors could be realized at a time, they set different priorities (Kvavilashvili & Ellis, 2004).

The real-life/laboratory controversy is an illuminating example that even methods which have been the status quo for decades cannot satisfy all aspirations but require trade-offs. The initial impression that the traditional and ecological approaches are dichotomous opposites seems plausible measured against the technical possibilities of that time: The integrity and meaningfulness of tasks or stimuli may have been difficult to establish in controlled laboratory settings given that personal computers (PC) were a novelty (Wrigley, 1957). In order to apply experimental methods common for most branches of the natural sciences, many task were computerized in a reductionistic manner (Shamay-Tsoory & Mendelsohn, 2019). Classical paradigms like Eriksen and Eriksen's (1974) flanker-task and Posner and colleagues' (1978) spatial cueing paradigm share that they measure processes highly precisely, in isolation, and strictly control for factors that are currently to be excluded from the examination. Yet due to the high experimental control maintained in these settings, their informative value about everyday functions is limited. Confounding factors which seem relatively irrelevant to the variable under investigation in sterile laboratory environments might decisively alter its function in real life (Nastase et al., 2020). Thus, to disentangle everyday human functioning, findings from these conditions form the empirical basis but need re-evaluation under multimodal, dynamic characteristics innate to real-world experiences (see e.g., Nastase et al., 2020; Parsons, 2015). These very characteristics are attributed to

VR applications as well, which is why VR is proposed as a methodological tool to increase ecological validity of psychological research (Felnhofer et al., 2015; Parsons, 2015). More than that, the expectation arose that VR applications resolve the trade-off between experimental control and ecological validity (Kothgassner & Felnhofer, 2020): Instead of puzzling how to push both into equilibrium, they are no longer cast into the two bowls of the same scale but can be manipulated independently. Accordingly, VR-based experiments are a meaningful enhancement to refine previous insights gained from artificial laboratory studies and further unravel everyday life.

1.3 Virtual reality as a methodological tool

In the past decades, Virtual Reality evolved as a broad term, covering multiple applications, technologies and characteristics (Kardong-Edgren et al., 2019). Modern definitions overlap in that VR is understood as a computer-generated environment (Cipresso et al., 2018; Riva, 2006), usually referring to a panoramic and three-dimensional environment (Mazuryk & Gervautz, 1996). However, monoscopic or non-panoramic virtual environments (VEs) are oftentimes labeled VR as well (e.g., Rodrigues et al., 2018; Serino & Repetto, 2018). The surrounding world is not meant to be augmented by use of VR systems but replaced (Carmigniani et al., 2011), isolating the user from their real-world surroundings (Speicher et al., 2019). Therefore, VR is supposed to create the illusion that the virtual surroundings are the only ones existing (Costanza et al., 2009) and to promote a feeling of presence within the VE (Slater & Wilbur, 1997). Moreover, VR is at least to some extent interactive, oftentimes implemented by means of head-tracking (Cipresso et al., 2018; Riva, 2006). In summary, the three key characteristics innate to VR are the immersiveness of the hardware, the interactivity of the VE, and a high sensation of presence or "being there" experienced by the user (Cipresso et al., 2018; Mütterlein, 2018) and will be described in more detail in chapter 1.3.1. Since there is no universally accepted definition of VR to date, the notion of VR as a computer-generated environment characterized by immersiveness, presence and interactivity is used as a working definition in the context of this dissertation.

Also due to the broad and varying definitions of VR, there are several groups of devices and software grouped together and associated with the label. Scientific literature mainly differentiates between so-called headset-VR, simulator-VR and desktop-VR systems (for reviews see e.g., Smith, 2019; Takac et al., 2021). While headset-VR and simulator-VR are likewise comparable in visual features and proprioceptive matching (e.g., 3D-360° view, head-tracking), referring to desktop setups as VR is not without controversy, as such setups make use of conventional monoscopic monitors and input devices, e.g., mouse, keypad and joystick (Smith, 2019; Takac et al., 2021). They correspond to standard setups used in psychological research and are at most semi-immersive compared to sophisticated VR systems (Takac et al., 2021). Accordingly, desktop-VR setups will be referred to as conventional laboratory settings or conventional computer settings further on. For a historical overview of VR's background and a more in-depth differentiation of the three current, overarching systems, please see appendix 5.4.

1.3.1 Key characteristics of Virtual Reality

Before VR experiences became a tangible concept in psychological research, they were first described in science fiction: The most iconic movie which is hitting the nail almost too hard on the head is *The Matrix* (Wachowski & Wachowski, 1999): Except for a relatively small group of resisters, the mankind of the 21st century lives in a perfectly simulated world – completely unaware of it. They experience the simulated world with all their senses; *The Matrix* can be viewed, heard, smelled, tasted, and touched. At least, that's what people are convinced of. In its all-embracing and (close to) perfect nature, the idea of *The Matrix* still exceeds most of today's technical possibilities; especially considering that it stimulates the nervous system through a wire connection to the human brain. However, it also encompasses the key characteristics innate to current sophisticated VR systems: Immersion, interactivity and the sensation of presence (Mütterlein, 2018, see Figure 1, p. 15).

Immersion refers to the properties of the VR hard- and software[4], and denotes the technology's capability to create an "inclusive, surrounding, extensive and vivid illusion of reality to the senses" (Slater & Wilbur, 1997). In particular, immersive VR systems are able to isolate the user from sensory input provided from the physical world (Cipresso et al., 2018; Sousa Santos et al., 2009) while preserving the multimodality and dynamics innate to real world environments (e.g., Parsons, 2015). On

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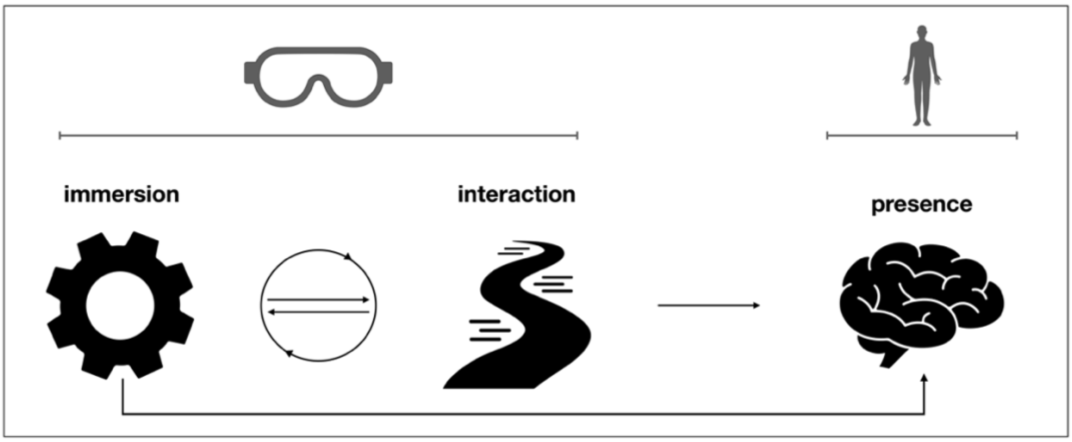
[4] In the early days of VR research, immersion was in some instances defined as a psychological concept. Today, immersion refers relatively uniformly to objective system properties (Nilsson et al., 2016; Witmer & Singer, 1998).

the perceptual level, immersive VR can be designed in such a way that the distal cues within the VE correspond to naturalistic ones (see Parsons, 2015), e.g., in terms of a stereoscopic and panoramic view (3D-360°). Relevant depth stimuli are retained and do not need to be recalculated by the brain from monoscopic cues (Dan & Reiner, 2017; Schöne et al., 2021). As a result, VR provides a wider range of visual information about the surrounding environment to the sensory channels (Wilson & Soranzo, 2015) and potentially enables a more realistic proximal stimulus. Most VR environments additionally address the auditory sensory channel and create a spatial soundscape, some additionally offer motion, haptic, and/or olfactory cues (Wilson & Soranzo, 2015). Thus, due to the synchronous stimulation of multiple sensory channels, the sensorimotor system is engaged more profoundly by VR than in conventional environments (Bohil et al., 2011), thereby, e.g., promoting mental processing speed of stimuli within the environment (Hecht et al., 2006; Wilson & Soranzo, 2015).

Figure 1.

Key characteristics of Virtual Reality and their interdependencies.



Note. VR characteristics are divided into objective technology properties (immersion, interactivity) and subjective user properties (presence). The technological characteristics have a reinforcing effect on the sense of presence. In contrast, presence has no causal influence on the technology (see e.g., Nilsson et al., 2016; Slater & Wilbur, 1997).

Moreover, immersion increases with appropriate implementation and representation of pictural and physical laws (Slater & Wilbur, 1997). This also points to the need of proprioceptive matching to achieve an immersive experience: The lower the lag between one’s own body movements and the VE's feedback, e.g., adjusting the perspective according to the user’s head tilt, the higher its vividness as it allows for egocentric perception of the environment (Nilsson et al., 2016). Well-tuned proprioceptive matching and the egocentric perspective simultaneously offer interactive elements.

Interactivity may be considered a subcomponent of immersion but is a defining VR characteristic in its own right as well (Figure 1, p. 15; see also Mütterlein, 2018). In addition to head movements being tracked, the environment can be manipulated and navigated through, e.g., by use of hand-held controllers (Schubert et al., 2001), enabling the user to take an active role within the VE (Serino & Repetto, 2018; Slater & Wilbur, 1997). Adding interactive features beyond head- and controller-tracking, like hand-tracking up to full-body tracking, facilitates self-engagement in the VE (see Lin, 2017). Optimally, the VR would include an avatar that corresponds to the user's movements and actions (Slater, 2009).

More broadly, interactivity also refers to the narrative or plot of the VE (Slater & Wilbur, 1997). Going beyond mere stimulus presentation, not only do single objects offer high fidelity and rich sensory cues, but the whole environment can be designed to offer a vivid and meaningful context relevant to the presented objects and events (Parsons, 2015; Reggente et al., 2018; Serino & Repetto, 2018). Hence, VR is not restricted to perceptual stimulation but offers conceptual information as well. For example, seeing a VR spider *versus* the task to open a VR drawer which is *supposed* to contain a spider both elicits fear (see Diemer et al., 2015). In this context, interactivity contributes to the application of conceptual knowledge to the VE. Spinning the thread of the spider in the VR drawer further, participants might decide against opening it, check whether it is tightly closed or walk as far away as possible to prevent a close encounter with the spider. Thus, the immersive nature of VR facilitates not only an egocentric perspective on the perceptive level but also egocentric processing and acting within the virtual surroundings and unfolding events (Riva, 2006). In contrast, conventional laboratory settings present the experiment’s content on simple screens or monitors, allowing observation and view of the content like looking through a window: The observer is separated from the depicted content and events (at least) by a glass barrier (Slater & Wilbur, 1997). Thus, the stimuli and tasks shown are at best proxies of real events but cannot reflect or predict them to the fullest possible extent (Nastase et al., 2020; Schöne et al., 2015). Conversely, VR enables the user to step through the looking-glass and experience the unfolding events as an active participant (Slater & Wilbur, 1997).

The more tightly the VR envelopes the user, and the more it involves the user by interactions, the stronger the illusion to be present within the VE is (Cipresso et al., 2018, see also Figure 1, p. 15; Diemer et al., 2015; Nilsson et al., 2016; Slater, 2009). While immersion and interactivity as properties of the VR system itself can be objectively determined (Nilsson et al., 2016), presence is a psychological state of mind and refers to the sensation of actually being in a certain (virtual) space; in short it is the sense of "being there" (Sheridan, 1992; Slater et al., 1994). Accordingly, the sense of presence diminishes the knowledge of not being in the physical reality, or at least reduces the meaningfulness and awareness of that knowledge (Kisker et al., 2021a; Schubert et al., 2001). This sensation can even establish beside the confident knowledge that it is not possible to physically be at a certain place (place illusion; Slater, 2009). In everyday life, presence is a state of consciousness that is hardly ever reflected upon (Slater, 2004). On the contrary, it is rather a break of feeling present, the absence of presence, that leads to a conscious perception of this state (Ijsselsteijn et al., 2001); or how Leonardo DiCaprio very accurately put it in the movie *Inception*: “Our dreams feel real while we're in them. It's only when we wake, we realize things were strange” (Nolan, 2010). The same might hold true for VR experiences: The stronger the sensation of actually being in the VE, of being able to interact with the virtual surroundings, affecting the plot and moving around, the greater the chances that the user will feel, think and behave within the VE as if they were in an equivalent real-world environment (Blascovich et al., 2002; Kisker et al., 2021a). As a consequence, the feeling of being personally and directly affected by the environment and events arises (Lin, 2017; Slater, 2009). The spider in the drawer thus becomes not only tangible but can even affect the participants themselves. Individual actions and reactions take on a meaningful significance as they affect the perceived environment and alter the course of events (Riva, 2006). Accordingly, two essential consequences of using VR applications, and major advantages compared to conventional settings, are the egocentric perception and processing of the VE (Lin, 2017; Riva, 2006), as well as behavioral realism within it (de la Rosa & Breidt, 2018; Kisker et al., 2021a).

1.3.2 The premise of ecological validity

Although some argue that it was exaggerated and too unspecific to speak of increasing the ecological validity of psychological research *per se* (Holleman et al., 2020), the phrasing may nevertheless fit the application of VR as a methodological tool: Ecological validity might refer to either (a) the experimental stimuli, (b) the experiment's context or (c) the task, response and behavior within the experiment (Holleman et al., 2020). However, measured against the previously outlined key characteristics, VR's application can, in principle, contribute to improvements in all of these dimensions. The experimental stimuli can be designed three-dimensionally, graphically high-quality and interactable (Parsons, 2015). Natural features of real objects are mimicked, such as stereoscopic depth stimuli, proportions and shading. The experiment's context, which is classically the laboratory with the experiment restricted to the screen, can be completely replaced by a naturalistic but controlled 360°-environment. The ecologically valid design of the task is in the hands of the researcher, but VR provides the potential for designing meaningful tasks relevant to everyday life, for instance by enabling congruent physical locomotion. Yet the participant's response and behavior are a function of the immersive VR itself, particularly facilitated by egocentric perspective and processing, as well as by behavioral realism (de la Rosa & Breidt, 2018; Kisker et al., 2021a; Lin, 2017; Riva, 2006). Based on these characteristics and the current state of research (e.g., Kothgassner & Felnhofer, 2020; Pan & Hamilton, 2018; Parsons, 2015), the synopsis at hand posits that the application of VR offers higher ecological validity than conventional standard laboratory settings as a premise.

1.4 Through the looking-glass and what they found there[5]

As previously outlined, VR setups can be applied to simulate natural real-world environments. They might provide major contributions to sophisticated understanding of everyday human functioning (Bohil et al., 2011; Pan & Hamilton, 2018; Parsons, 2015). However, VR-based research needs to be put into perspective with respect to existing research findings. Under the premise that VR applications offer higher ecological validity but equal levels of experimental control compared to conventional setups (e.g., Kothgassner & Felnhofer, 2020; Parsons, 2015), it needs to be determined whether VR setups result in experimental outcomes equal to those obtained under conventional settings or whether such outcomes differ significantly. In the case that outcomes from VR and conventional settings are equivalent, VR would not be a significant gain on balance, albeit different in application and offering new methods to replicate and generalize previous findings. However, if significant differences would emerge, VR setups would add high value for psychological research to investigate human functioning in a more natural way. Even if VR did not resemble reality more closely compared to conventional settings, differences between both approaches would indicate that previous results cannot be generalized without restriction to real-world processes, as the research outcome heavily depended on the method of choice (see e.g., McDermott et al., 2009). Following this line of thought, a series of VR studies will examine whether previous research findings can be generalized to VR applications. For this purpose, standard paradigms will be adapted to VR conditions and well-established research findings will be evaluated (see Table 1, p. 20). Fundamental cognitive-affective processes are suitable as a starting point for the evaluation process. In particular, emotional processing of multifaceted experiences and remembering them take pivotal roles in everyday life. The following sections (1.4.1, 1.4.2) aim to outline the related state of VR-based research and the dependent variables that will be included, with reference to their interpretation in classical studies. The purpose herein is not to extend the applied standard paradigms and research findings in their own right but to provide an overarching empirical basis and insights into whether and which differences between both kinds of experimental setups are associated with increasing ecological validity by use of VR as an experimental tool.

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[5] Referring to Carroll's sequel "*Through the looking-glass and what Alice found there*" (Carroll & Tenniel, 1899).

Table 1.

Overview of psychological standard paradigms and their translation to VR conditions.

Study	Standard paradigm	Adaption to VR	Dependent variable
Study 1.1 (Schöne et al., 2021) labeled: *motivation study*	Emotion elicitation paradigm using the IAPS: *affective rating of stimulus material* (e.g., Lang et al., 1997)*; electrophysiological recordings during picture presentation* (e.g., (Hewig et al., 2004)	Use of 3D-360° video footage as stimulus material	Frontal alpha asymmetry, presence
Study 1.2 (Schöne et al., 2021) labeled: *free recall study*	Free recall task: *recalling previously encoded stimuli without any cues* (e.g., Shiffrin, 1973)	Use of 3D-360° video footage as stimulus material	Retrieval success, presence
Study 2 (Kisker, Lange, et al., 2021) labeled: *cave study*	Approach-avoidance task: *pulling or pushing a joystick in response to a picture* (e.g., Rinck & Becker, 2007)*; electrophysiological recordings during stimulus presentation* (e.g., Hewig et al., 2004)	Exploration of either a negative or neutral mixed reality (MR) cave; encounter with a werewolf or a sheep that needs to be run past	Frontal alpha asymmetry, full-body behavior, subjective experience, presence
Study 3 (Kisker et al., 2020) labeled: *theta old/new study*	Recognition memory task: *distinguishing previously encoded stimuli from new ones* (e.g., Tulving & Thomson, 1971)	Use of 3D-360° video footage as stimulus material	Theta old/new effect, retrieval success, presence

Note. Each paradigm is associated with well-established measures that will serve as a benchmark for the comparison between the respective groups, as outlined in 1.4.1 and 1.4.2. The studies' labels are assigned to facilitate the readability of the following sections and the discussion.

1.4.1 Emotional responses to virtual worlds

To study the foundations of emotional responses, researchers are dependent on eliciting them on demand in the laboratory. For this purpose, conventional emotion elicitation paradigms confront participants with affective stimulus material. The most classical implementation of such paradigms is the presentation of affective footage on a computer screen. To standardize these settings, databases like the *International Affective Picture System* (IAPS; Lang et al., 1997) have been created and validated. The IAPS is internationally available to all researchers, contributing to the standardization, replicability, and comparability of studies across laboratories. Consequently, it has been widely applied in emotion elicitation paradigms for decades (see Uhrig et al., 2016). Similarly accepted and practicable is the use of sounds (e.g., *International Affective Digitized Sounds* (IADS); Bradley & Lang, 1999) and films (Gross & Levenson, 1995; Uhrig et al., 2016). The latter offer, beyond aforementioned materials, the possibility to stimulate multiple sensory modalities and represent more dynamic stimuli: Instead of a static impression, a narrative and complex event is conveyed (Gross & Levenson, 1995; Uhrig et al., 2016). Therefore, films are thought to be more realistic compared to pictures, even though their capability to elicit emotions in laboratory settings is relatively similar (Uhrig et al., 2016). Yet films are thought to offer higher ecological validity (Gross & Levenson, 1995). Therefore, the studies included in this dissertation used videos instead of photographs as stimulus material.

The responses to affective stimuli have commonly been measured using the dimensions valence, arousal and approach-avoidance, whereas the former two are usually evaluated simultaneously (Mauss & Robinson, 2009). Emotional responses likewise comprise physiological and behavioral components (Bradley, 2000; Bradley et al., 2001), but the most common and frequently used method to assess emotions is the subjective rating of arousal and valence by the participant themselves (Bradley et al., 2001; Mauss & Robinson, 2009; Uhrig et al., 2016). Although conventional methods effectively induce and evaluate emotions in laboratory settings (see e.g., Bradley et al., 2001; Mauss & Robinson, 2009; Uhrig et al., 2016), these methods are subject to the prerequisite that being confronted with a stimulus displayed on a conventional screen triggers the same response as encountering the stimulus in real-life. To exaggerate, the image of an attacking wolf is supposed to evoke the same emotional response and processing as a real wolf physically attacking the participant in the real-world. Obviously, stimuli that are only an abstract representation of their real-world equivalent, such as photographs, may elicit responses that predict the real-world equivalent of the expected response with some probability, but they are substitutional indicators at best: They are placeholders or reminders of real-world entities and need to be evaluated by the participant (Schöne et al., 2015). Such cues leave a trace of "pretending-as-if": Rate how you would feel encountering the scene in the photo if it happened in reality; react as fast as if your speed was actually pivotal for your own safety. Accordingly, there is a discrepancy between the response to the representation and its real-world counterpart that has not yet been precisely determined.

In contrast to these traditional approaches, VR applications might be used to determine or even close this gap. It was demonstrated that VR is capable to elicit emotional responses *per se* (e.g., Felnhofer et al., 2015), increasing its relevance as an experimental tool. Changes in distinct affective states were primarily achieved through the VE's context design. For example, participants reported joy when 'being' in a park on a sunny day (Felnhofer et al., 2015), anxiety in a gloomy park at night (Felnhofer et al., 2015; Riva et al., 2007) and awe when looking at snowy mountains (Chirico et al., 2018). Going one step further, initial studies propose that emotional responses elicited in VR significantly differ from those elicited using conventional presentation modes, in particular conventional 2D-monitors (e.g., Gorini et al., 2010). Even more, the former were found to resemble reactions to real-world experiences more closely, or are even identical (Gorini et al., 2010; Higuera-Trujillo et al., 2017). For instance, Higuera-Trujillo and colleagues (2017) demonstrated that both 360° photos and immersive VR approximate real-world responses more closely than photographs. The assessment of emotional responses to real, virtual, and photographed food followed the same trend (Gorini et al., 2010). Both studies emphasize a crucial advantage of using VR in psychological research: Humans are no passive observers, they try to understand and actively manage the situations they encounter (Kihlstrom, 2021). In stark contrast to previous approaches used to elicit emotional processes, responses to VR experiences are not mediated but directly correspond to the encountered entity (Chirico & Gaggioli, 2019; Gorini et al., 2010; Higuera-Trujillo et al., 2017). Hence, VR offers the opportunity to assess a holistic reaction, enveloping affective, psychophysiological and behavioral components of a realistic emotional response.

Current findings, however, are largely based only on participants' subjective ratings of affective states as illustrated by a recent review on mood induction using VR. While all of 61 included studies, which applied non- to fully immersive setups, collected data on subjective affective responses, only about half included psychophysiological responses as well (Bernardo et al., 2020), focusing on responses of the autonomic nervous system (ANS) sensitive to arousal. Specifically, heart rate (HR) and skin conductance response (SCR) increase with arousal (Bradley, 2000). As manifested in these psychophysiological correlates, the emotional responses to VR settings have been found to resemble responses to equivalent real-world experiences (Chittaro et al., 2017; Gorini et al., 2010; Higuera-Trujillo et al., 2017; Parsons et al., 2013), yet both measures are independent of the experience's valence

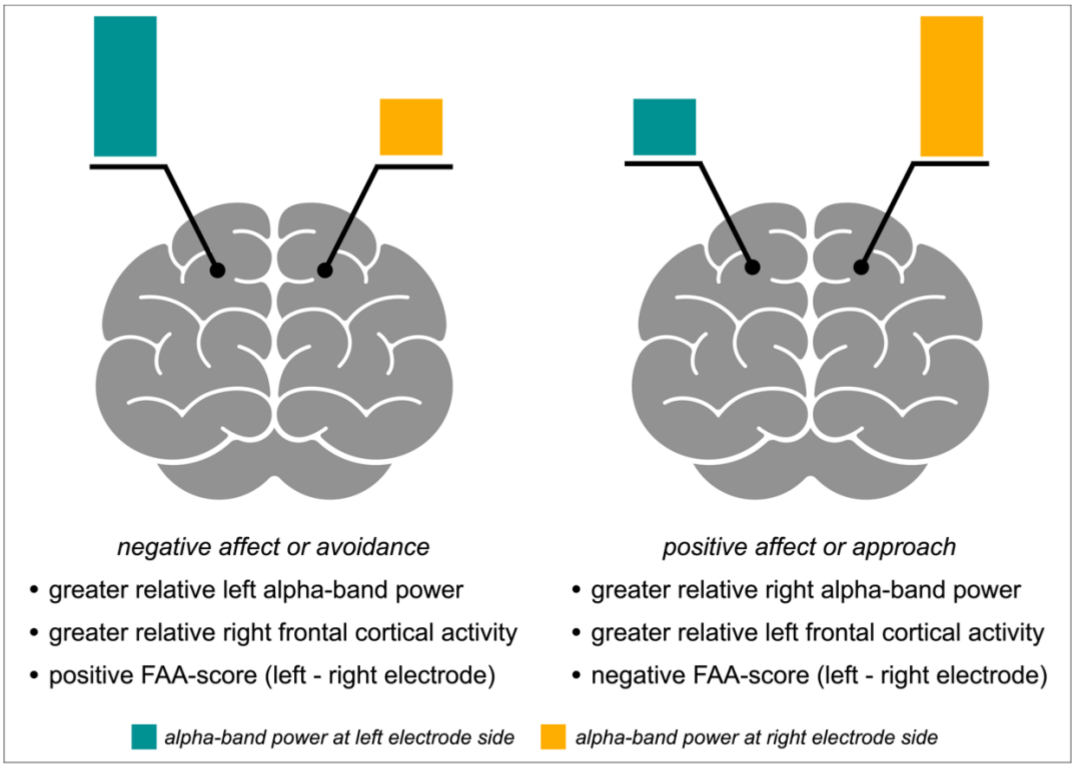
(Bradley, 2000). Thus, surprisingly, VR's capability to elicit holistic responses has not been exploited to its full potential. Although previous findings are promising, more complex objective comparisons of VR settings to conventional or real-world conditions have been neglected. In contrast to evaluations by the participant, the electrophysiological response of the brain provides an unvarnished foundation for comparison of conventional laboratory and VR conditions and might deliver more profound indications of the perceived valence of a stimulus.

A possible objective, electrophysiological benchmark for the hedonic valence of the stimulus material lies in the alpha-band power (8-13Hz; Berger, 1929; see also Davidson, 2004; Harmon-Jones et al., 2010; Lacey et al., 2020). The alpha-band's power is an indicator of the strength of this specific rhythmic activity within the total EEG signal. It reflects synchronous oscillations, i.e., fluctuations in the excitability of neuron populations in a certain frequency (e.g., Ward, 2003). More specifically, a decrease of alpha-band power is linked to increases in cortical activation (Allen et al., 2004; Harmon-Jones et al., 2010). The ratio between left and right frontal alpha-band power (frontal alpha asymmetry; FAA) has been found to correlate with emotional and motivational processes, and has thus been widely associated with both, valence and approach-avoidance (Harmon-Jones et al., 2010; Mauss & Robinson, 2009). Initially, relatively greater left frontal alpha-band power was associated with negative affect, whereas relatively greater right frontal alpha-band power was related to positive affect (Davidson, 1979, 2004; see also Figure 2, p. 24).

However, growing evidence excluded valence from the role of FAAs and mapped the corresponding FAAs to the approach-avoidance dimension (for a review see e.g., Harmon-Jones et al., 2010; Hewig, 2018; see also Figure 2, p. 24). This was predominantly prompted by the observation that anger as a negative affective state related to relatively greater right frontal alpha-band power (e.g., Gable & Harmon-Jones, 2008). More recent models related relative greater left frontal alpha-band power to avoidance motivation and, vice versa, relative greater right frontal alpha-band power to approach motivation (motivational direction model, e.g., Harmon-Jones et al., 2013). This link has been demonstrated, e.g., during resting state (e.g., Quaedflieg et al., 2015; Thibodeau et al., 2006), affective facial expressions (e.g., Coan et al., 2001), in response to affective pictures (e.g., Adolph et al., 2017; Schöne et al., 2015) and films (e.g., Papousek et al., 2014).

Figure 2.

Schematic illustration of frontal alpha asymmetries and their common interpretation.



Note. The illustration does not claim anatomical correctness but is purely schematic. The interpretation (italics) of the respective FAAs is derived from the models on the role of the FAA as outlined in 1.4.1 (Harmon-Jones et al., 2010; Harmon-Jones & Gable, 2018; Hewig, 2018; Rodrigues et al., 2018).

Although a recent review indicates that top-down control on emotion regulation may account for these findings (Lacey et al., 2020; see also Schöne et al., 2015), the link between FAA and motivational direction is a meaningful starting point to examine emotional processing depending on the presentation mode. Thus, Study 1.1 (labeled *motivation study,* see Table 1, p. 20) aims to unravel whether emotional-motivational mechanisms deployed under VR conditions correspond to those under conventional laboratory settings, or whether significant differences between both modes of presentation can be found on the electrophysiological level. In particular, the electrophysiological response to VR might provide deeper and more complex insights into the emotional-motivational processing of realistic experimental stimuli and settings going beyond arousal. For this purpose, the same video footage will be displayed either in a fully immersive 3D-360° VR condition or in 2D on a large screen. Both groups wear the same HMD to rule out that wearing the HMD itself promotes differences in the electrophysiological response. FAAs as indicators of motivational directions serve as a benchmark for the evaluation. The *motivation study* also contributes to the development of a database resembling *IAPS* (Lang et al., 2008; Lang et al., 1997) but consisting of 3D-360° footage, which will be made internationally available to researchers as standardized stimulus material (*Library for Universal Virtual Reality Experiments (luVRe),* Schöne et al., 2021).

The *motivation study*'s approach addresses the affective and physiological component of the emotional response by assessing electrophysiological correlates. In the behavioral component, emotion and motivation are intrinsically intertwined. As their shared Latin word stem "movere" indicates, both serve the purpose of setting the organism in motion to promote survival. The latter is, very generally speaking, achieved by adapting behavior in terms of either appetitive or defensive reactions (Bradley et al., 2001). In this line of thought, the appetitive system is associated with approach of nutrition, procreation and sustenance. In contrast, the defensive system responds to threat by avoiding illness, attack or contamination (Bradley et al., 2001; Lang & Bradley, 2010). These behavioral responses in terms of approach and avoidance are thought to be reflected in FAAs as well (Rodrigues et al., 2018). In particular, different models have linked relatively greater left frontal cortical activity, i.e., relatively greater right alpha power, with approach behavior (Harmon-Jones, 2003) and active behavior (Wacker et al., 2003, 2008). In contrast, these models linked relatively greater right frontal cortical activity, i.e., relatively greater left alpha power, to avoidance behavior (Harmon-Jones, 2003) and behavioral inhibition or conflict (Wacker et al., 2003, 2008).

However, these findings are based on highly controlled settings in which behavior is limited to its proxies: In computerized approach-avoidance tasks, participants usually indicate whether they want to approach or avoid a stimulus by pressing either one of two buttons on a keyboard or by moving a joystick (see e.g., Gable & Harmon-Jones, 2008; Rinck & Becker, 2007). Accordingly, participants have to evaluate which behavioral response would be intuitive for them in the respective situation rather than intuitively executing that exact behavior. Initial studies ventured into more naturalistic and rich settings by inclusion of multiple sensory inputs (Brouwer et al., 2011) or by the use of computer games instead of static images (Rodrigues et al., 2018). Those settings were sufficient to elicit and obtain FAAs as indicators of stress (Brouwer et al., 2011), and corresponding to the motivational direction model (Rodrigues et al., 2018). Yet both approaches were limited in the spectrum of behavioral responses, i.e., to keypad and joystick inputs.

In order to increase the ecological validity of such approach-avoidance tasks, Study 2 (labeled *cave study*[6]) implemented a mixed reality (MR) design in which participants explored either a neutral or a frightful cave. Specifically, visual and auditory sensory inputs were delivered using a programmed VR environment via an HMD. The special features of the setup were, to begin with, that the haptic dimension was stimulated by a physical replica that was spatially aligned to the virtual cave. When participants touched the virtual walls, they touched a physical equivalent. Furthermore, the participants moved freely through the cave - every step, every head movement, every body rotation in the real world was translated to the movements in the virtual world (see Study 2 for details). Accordingly, the *cave study*'s aim was to facilitate naturalistic behavioral responses and to put to the test whether FAAs as electrophysiological correlates of approach and avoidance behavior obtained under conventional laboratory conditions would transfer to highly interactive VR setups.

The comparison between a neutral cave and a negative cave was deliberately chosen as fear is associated with strong, complex, and intuitively recognizable behavioral responses. As Agent Smith points out in *The Matrix*, humans are hardwired on negativity: "Did you know that the first Matrix was designed to be a perfect human world? Where none suffered, where everyone would be happy. It was a disaster. No one would accept the program. . . . The perfect world was a dream that your primitive cerebrum kept trying to wake up from" (Wachowski & Wachowski, 1999). It is an evolutionary adaption to pay great attention to negative events, especially threats, to avoid risks to life (Cacioppo et al., 2014). Accordingly, behavioral adaptations such as the flight-or-fight response (Cannon, 1922), or slowing ones gait to increase vigilance (Rinck et al., 2010) are mandatory to overcome threats. The neutral condition was essential to establish a baseline for the behavior that results from the exploration of a VR environment *per se*, whereas the negative condition was designed to reveal behavioral adaptations to a

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[6] The label "*cave study*" literally refers to the local setting aka a virtual cave/rock den. It is not to be confused with simulator-VR-studies using *Computer Aided Virtual Environments (CAVE;* see e.g., Smith, 2019 and appendix 5.4.2).

frightening environment. Therefore, the comparison between two VR conditions was chosen instead of the comparison of a VR condition and a conventional condition.

The *cave study* was conducted under the premises that, firstly, FAAs can generally be measured online during VR exposure (see Study 1.1; see also Lange & Osinsky, 2020 for mobile EEG application) and, secondly, that VR setups enable adequate, specific induction of fear. Previous research provides evidence that VR elicits both fear mediated by context *per se* and fear of specific cues, manifested in psychophysiological measures, verbal expressions and behavioral expressions (Felnhofer et al., 2014, 2015; Lin, 2017). Hence, as VR enables realistic responses to threatening situations (Kisker et al., 2021a), it can be assumed that participants might physically retreat from a perceived danger, if the study design enables them to do so. Thus, to test whether previous links between FAA and emotional-motivational processes can be generalized to immersive setups, the electrophysiological response was measured during the cave exploration using a mobile EEG system. The novelty and incremental value of the study lies particularly in the combination of unmediated behavioral response and the simultaneous collection of objective measures within a fully immersive VR environment. Based on previous findings (Rodrigues et al., 2018), fear behavior was proposed to be associated with avoidance motivation, and thus with relatively greater right frontal cortical activity. However, to our best knowledge no study has collected electrophysiological correlates of approach and avoidance under similarly immersive conditions. Completely different outcomes might result from increasing ecological validity. For example, the neutral condition is not proposed to elicit a distinct motivation or FAA. Yet every situation we encounter in everyday life elicits some response: Even the absence of feeling a specific emotion, i.e., feeling neutral, can be denoted as a response indicating that a situation is not of particular interest, exciting or personal significance (Gasper et al., 2019) and might elicit altered responses in VR settings compared to conventional settings. This altered affective perception of, and emotional response to an experience also has a hand in how it is remembered (see e.g., Samide et al., 2020).

1.4.2 Remembering laboratory and virtual experiences

The ability to remember past events and entities is essential to everyday life (Abram et al., 2014) and sometimes considered unique to human beings (Gilboa et al., 2004). These memories of life events are usually classified as episodic memory (EM; Tulving, 1983). Two fundamental processes underlying human memory are the free recall and the recognition of past events, which are reflected in standard memory tasks of the same name. Both free recall tasks and recognition memory tasks fulfill the purpose of quantifying memory performance and traditionally follow a biphasic procedure. The first phase coincides in both paradigms: Participants either incidentally or intentionally encode a set of items, e.g., a word list (e.g., McDermott et al., 2009; Shiffrin, 1973). In both cases, the items are to be retrieved in the next phase but use different strategies. In free recall tasks, participants are asked to recall the items without any cues and in any order (Shiffrin, 1973). In recognition memory tasks, the encoded items are mixed up with unknown ones and participants are asked to distinguish items according to whether or not they remember them from the encoding phase (e.g., Jacobs et al., 2006; Klimesch et al., 1997). Both follow the approach of laboratory-based methods (McDermott et al., 2009): They make use of memories artificially created in the laboratory by inducing engrams that are often referred to as micro-events (e.g., Cabeza et al., 2004). Like emotion elicitation paradigms, these memory tasks presuppose that, on the one hand, the encoding of the stimulus material corresponds to encoding processes in everyday life, and on the other hand, that the retrieval of the resulting engrams corresponds to the retrieval of everyday experiences (Gilboa, 2004; McDermott et al., 2009).

In the light of the real-life/laboratory controversy (see 1.2), it has been increasingly questioned whether real-world memory processes can be represented by laboratory EMs (McDermott et al., 2009). Autobiographical methods are often proposed as a more realistic counterpart to the latter. They rely on the recall of personal experiences. Pictures or words used in these paradigms only serve as cues to remember an event from one’s own past. For example, participants are given the word ‘dog’ and are supposed to recall an event from their own life which they associate with it. While the EM is proposed to encode experiences in their spatial and temporal context (Tulving, 1983) and relates to conventional laboratory tasks (Cabeza et al., 2004; McDermott et al., 2009), autobiographical memories (AM) extend such engrams by increased self-involvement in, and personal relevance of, the remembered experiences

(Conway, 2005; Roediger & Marsh, 2003; see Study 3). Particularly the comparison of both approaches fuels the debate that laboratory memories do not adequately represent real-life memories. To date, several studies dissociated EM as assessed by laboratory approaches and AM based on their electrophysiological correlates. Although the respective neuronal networks overlap to some extent, it particularly sticks out that AM tasks correspond to more pronounced activation of brain regions associated with emotional and self-referential processing (McDermott et al., 2009). Moreover, AMs create a quick and intuitive feeling of rightness, while laboratory-based EMs require more deliberate effortful monitoring to check for inconsistencies or errors (Gilboa, 2004). Correspondingly, autobiographical tasks are associated with activation of the default mode network (DMN) during successful retrieval, whereas conventional tasks primarily activate the frontoparietal control network (Chen et al., 2017).

These findings reinforce that the choice of method has severe impacts on the conclusions drawn from memory research (Cabeza et al., 2004; Chen et al., 2017; Gilboa, 2004; McDermott et al., 2009) and it seems intuitive to prefer AM approaches to study everyday memory. However, like other naturalistic or ecologically valid approaches, autobiographical tasks are criticized for their lack of experimental control. The most critical limitation is that it cannot be controlled in any way which exact events are remembered, whether the memory matches the genuine experience or, in extreme cases, whether the participant confabulates unknowingly or knowingly. Moreover, most AM tasks implement recall tasks only, thus leaving correct and false memories inseparable (McDermott et al., 2009). Initial approaches to overcome these limits applied controlled autobiographical conditions: Cabeza and colleagues (2004) asked their participants to take photos of specified locations (creating real-world memories) and to view pictures of these locations taken by other participants (creating laboratory memories). In a delayed recognition memory task, they were shown their own pictures mixed up with photos taken by others. Differentiating those photos required detailed context recall and allowed to determine retrieval accuracy (Cabeza et al., 2004). This approach definitely constitutes a methodological advancement but still leaves a number of factors uncontrolled: For example, it was not controlled for how long participants stayed at the locations, whether they examined them closely or only briefly passed by, whether they met other people there, whether and how well they knew the locations before the photography task or visited them again before accomplishing the recognition memory task. Although participants visited and encoded the same locations, the experience might have differed, e.g., in its emotional content or personal relevance both crucial to AM (Conway, 2005; Roediger & Marsh, 2003).

In contrast to the aforementioned methods, VR does not need to balance ecological validity and experimental control but can turn both dials to a high level (Kothgassner & Felnhofer, 2020; Parsons, 2015). Current VR technology offers the possibility to create a variety of ecologically valid scenes. For example, real-world environments can be filmed with respective VR cameras to serve as stimulus material. The resulting VR environments are not limited to isolated stimuli but can be context-rich scenes including unfolding events (see Study 1 and appendix 5.4.2 for details). Hence, VR environments encompass precisely those spatial and temporal features that are considered defining for EM (Serino & Repetto, 2018). Going beyond EM, the egocentric perspective and processing, as well as higher emotional salience (see 1.4.1, Study 1.1 and Study 2) might contribute to increases in self-relevance (Kisker et al., 2021b; Schöne et al., 2019), which is formative for the memory of everyday experiences, i.e., AM (Conway, 2005; Greenberg & Rubin, 2003). While immensely increasing ecological validity over conventional settings, VR additionally delivers advantages over AM approaches as well, such as high control over immersive, vivid experiences and the ability to implement recall and recognition tasks.

Previous VR studies on human memory mainly focused on differences in retrieval success under immersive compared to non-immersive conditions. Overall, a superiority effect for VR conditions emerges: Participants who encode under VR conditions are subsequently more successful in retrieving the encoded information compared to, e. g., desktop-based encoding (e.g., Harman et al., 2017; Schöne et al., 2019, for a review see Smith, 2019). However, the data situation is inconsistent and despite the general trend there are also contradictory results. For example, Kisker and colleagues (2021b) did not replicate a generally superior retrieval of objects encoded in an interactive VR environment, but found evidence for altered retrieval mechanisms. While participants of the VR condition vividly recollected objects from the VE, participants of the PC condition rather reported a feeling of familiarity. Further studies found no difference in retrieval success between immersive and non-immersive conditions at all (Cadet & Chainay, 2020; Dehn et al., 2018; LaFortune & Macuga, 2016). Thus, to date it remains unclear under which circumstances VR experiences affect retrieval success, the mode of retrieval or both.

In order to further investigate under which circumstances increasing ecological validity by using VR leads to altered memory performance or processes, Study 1.2 (labeled *free recall study*) will implement a classical free recall task and Study 3 (labeled *theta old/new study*) will implement a classical recognition memory task. We refrained from interactivity beyond egocentric perspective and head-tracking as navigation tasks might promote spatial memory (Plancher et al., 2013) more strongly than the integrated components of EM and AM. Accordingly, both studies will make use of VR footage instead of a programmed VE.

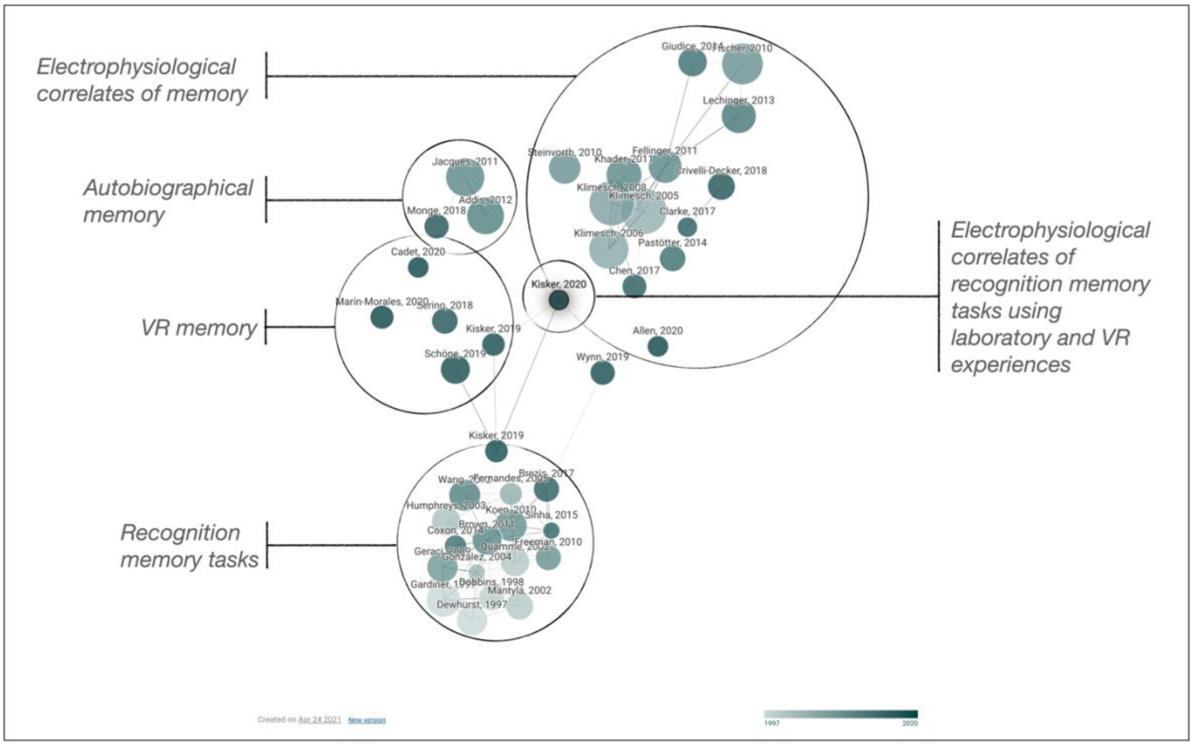
In detail, the *free recall study* aims to replicate the superiority effect concerning retrieval of VR experiences for multifaceted VR footage depicting real-world environments and events. Previous studies implementing free (Cadet & Chainay, 2020) or, more frequently, cued recall tasks (Bailey et al., 2011; Ernstsen et al., 2019) usually focused on objects depicted within VEs. Instead of passively presenting such objects on a screen as in conventional settings, most VR memory studies integrate the memory task items into congruent environments (Cadet & Chainay, 2020; Ernstsen et al., 2019; Harman et al., 2017). These applications resulted in variable effects on memory performance, with differences between groups partially only becoming apparent when controlling for the participant's gaming experience (Ernstsen et al., 2019) or usability of the applied VR technology (Harman et al., 2017). In contrast, the VR condition in the *free recall study* is intended to remain as close as possible to a conventional free recall task. To this end, VR videos are presented in randomized order during the encoding phase; only the mode of presentation is varied between groups. Doing so yields at least three predominant advantages: As a start, sticking close to the conventional setup and altering only the mode of presentation between groups provides a baseline for the potential superiority effect. Since all participants see the same stimulus material in the same quality, the cost or benefit to the memory performance of the immersive VR condition measured against a conventional PC condition can be traced back to the presentation in 3D-360°. In addition, participants are not required to have any prior VR experience or technical expertise to fully benefit from the immersive nature of the setting, rendering any possible distractions or interferences by technical hurdles void. Moreover, complex scenes, such as the VR footage, but also videos as stimulus material *per se* are less susceptible to primacy or recency effects than objects or words presented in isolation (Shiffrin, 1973). The study's approach follows the hypothesis that VR-based encoding improves memory performance. In order to quantify memory performance, participants are asked to recall the scenes they have seen without prior announcement. Using free recall, a distinct influence of the cues' modality on the groups' performance can be ruled out. For example, the PC condition might possibly profit from using 2D screenshots as cues, whereas the VR condition would undergo a change of dimensionality between stimuli and cue.

While the *free recall study* and most VR memory studies apply behavioral data to assess memory performance (Cadet & Chainay, 2020; Harman et al., 2017; Schöne et al., 2019) and mechanisms (Kisker et al., 2021b), the *theta old/new study* aims to further disentangle the incongruence of previous findings through investigation of electrophysiological correlates of recognition memory. Particularly studies investigating the electrophysiological correlates of VR experiences are very sparse (see Figure 3, p. 33). To the best of our knowledge, there is no other publication reporting the electrophysiological investigation of retrieval of engrams encoded within VR (for reviews see Bohil et al., 2011; Plancher & Piolino, 2017; Serino & Repetto, 2018; Smith, 2019). As Figure 3 illustrates, the electrophysiological correlates of memory *per se* and memories formed under VR conditions have so far been studied independently.

This state of research is particularly surprising with respect to the previous promising results based on the behavioral data. The memory superiority effect (Schöne et al., 2019) and altered retrieval mechanisms (Kisker et al., 2021b) have been considered as indicators of different memory systems underlying VR-based and laboratory-based engrams. In the light of the real-life/laboratory controversy, the retrieval of VR experiences has been linked to AM due to VR experiences' rich content and increased self-relevance (Kisker et al., 2021b; Schöne et al., 2019). This assumption would be even more profound if based upon objective, electrophysiological correlates of memory retrieval. One possible reason why VR experiences have so far fallen short in electrophysiological examinations might be the technical hurdle of combining sensitive EEG systems with VR hardware. Although the *motivation study* and the *cave study* will show that the online-assessment of electrophysiological data during a VR session is generally feasible, the *theta old/new study* (Study 3) circumvents this hurdle by varying the mode of presentation during the encoding phase only and subsequently recording EEG during the retrieval.

Figure 3.

Publications thematically connected to the theta old/new study (Study 3).



Note. The encirclements of the grouped publications roughly indicate the overall thematic assignment. Created by and adapted from http://connectedpapers.com, an empirically founded online tool that analyzes around 50.000 papers related to the original paper (here: Study 3) and selects those with the strongest connection, regardless of mutual citations (Eitan et al., 2020). Retrieved on 24.04.2021.

In detail, participants of the *theta old/new study* complete a recognition memory task after encoding either immersive VR footage or the very same stimulus material depicted in 2D on a screen (see *theta old/new study* for details). In order to evaluate the differences between the retrieval of VR experiences and laboratory micro-events beyond memory performance, the well-established theta old/new effect as an electrophysiological correlate of memory retrieval is examined. Theta-band oscillations (~4-8Hz, e.g., Nyhus & Curran, 2010) are broadly studied in recognition memory tasks and synchronize during mental activity (Klimesch et al., 1997). These synchronous oscillations are thought to enable interactions of the cortical-hippocampal network which, in turn, is associated with the encoding and retrieval of EMs (Nyhus & Curran, 2010). A consistently replicated and accordingly considered robust finding is the theta-band response to known and unknown stimuli (Guderian & Düzel, 2005; Hsieh & Ranganath, 2014; Klimesch et al., 1997; Nyhus & Curran, 2010). In particular, theta-band oscillations measured at sensors over frontal-midline regions synchronize in response to old stimuli and desynchronizes in response to new stimuli. The same trend has been reported when differentiating between old, remembered and new, non-remembered stimuli subsequent to either stimulus presentation (Klimesch et al., 2001) or the participants' response (Gruber et al., 2008). The theta old/new effect has primarily been associated with retrieval success. However, particularly of interest for Study 3 is the theta-band's association with the recollection of personal events (Guderian & Düzel, 2005), rendering it a meaningful benchmark to examine whether and how increased ecological validity alters cognitive processing by means of VR-encoded engrams. In conjunction, the alpha-band response is taken into consideration as an additional indicator of the underlying mechanisms. In contrast to the theta-band response, the alpha-band responds with desynchronization to mental activity, reflecting visual and attentional processing (Clayton et al., 2018; Klimesch et al., 1997) and memory load (Sauseng et al., 2009, see Study 3 for details). This ensemble of well-established electrophysiological markers of recognition memory is expected to provide profound insights into how retrieval differs as a function of the presentation mode during encoding.

1.5 Summary and outlook

The aim of this dissertation and the included empirical studies is to shed light on whether and which cognitive-affective research findings change and which remain unchanged when the ecological validity of the research method is increased. To this end, standard paradigms are translated to VR conditions (see Table 1, p. 20), providing higher ecological validity without limiting the experimental control. The empirical studies focus on either emotional or mnemonic processes and mechanisms. All studies except for the *free recall study* examine electrophysiological markers of the aforementioned cognitive-affective processes to enable an objective comparison and will be complemented by subjective and/or behavioral data. Moreover, all studies except for the *cave study* implement both a VR condition and a conventional laboratory condition. This approach follows the principle of replicating well-established effects obtained from conventional conditions to set a baseline for the same effect under VR conditions. In the *cave study*, two immersive MR conditions were implemented instead to set a baseline for generic behavior within the setup *per se* and to distinguish it from behavioral adaptations to a frightful VE.

The *motivation study* and the *cave study* focus on the emotional response to emotion-elicitation paradigms as assessed by canonical electrophysiological markers of the approach-avoidance dimension. Both will apply online-assessment of EEG data during the respective paradigm, capturing the immediate response to the affective content. The *motivation study* investigates whether FAAs differ depending on the mode of presentation, which is implemented either as immersive VR footage or the very same footage delivered via a virtual 2D desktop. The *cave study* will be extended by the behavioral component. To this end, full-body responses are enabled within this paradigm to examine holistic fear responses and to put to the test whether the respective FAAs linked to approach-avoidance behavior will translate from artificial responses to naturalistic ones.

The *free recall study* and the *theta old/new study* will focus on the comparison of mnemonic processes and mechanisms occurring under either conventional laboratory conditions or VR conditions. The *free recall study* aims to replicate the memory superiority effect of VR conditions over conventional conditions found in previous studies. Beyond that, complex scenes rather than isolated objects are to be remembered, increasing the naturalness of the utilized stimuli. Going one step further, the *theta old/new study* aims to differentiate retrieval mechanisms underlying VR-based and conventional laboratory experiences. The well-established theta old/new effect serves as a benchmark to check whether cognitive processes obtained under conventional conditions translate to immersive VR conditions. Potential differences between both conditions might provide more profound evidence for the assumption that VR experiences generate AMs in contrast to laboratory-induced EMs.

In the next step, the results of these studies are discussed with particular attention to whether and how increasing ecological validity alters the standard findings expected on the basis of the previous research background. Although it is in the nature of the studies to provide further insights into the effects under consideration as well, the primary focus of this dissertation is to compare results obtained under conventional or VR conditions and to identify possible sources of these potential differences.

2. Empirical publications

This dissertation includes the following empirical publications:

Study 1.1 & 1.2:

Schöne, B., **Kisker, J.**, Sylvester, R. S., Radtke, E. L., & Gruber, T. (2021). Library for universal virtual reality experiments (luVRe): A standardized immersive 3D/360° picture and video database for VR based research. *Current Psychology*, 1-19.

Study 2:

Kisker, J.*, Lange, L.*, Flinkenflügel, K., Kaup, M., Labersweiler, N., Tetenborg, F., Ott, P., Gundler, C., Gruber, T., Osinsky, R., & Schöne, B. (2021). Authentic fear responses in virtual reality: A mobile EEG study on affective, behavioral and electrophysiological correlates of fear. *Frontiers in Virtual Reality*, 106.

Study 3:

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2.1 Study 1.1 & 1.2: *Library for universal virtual reality experiments (luVRe): A standardized immersive 3D/360° picture and video database for VR based research*

Abstract

Virtual reality is a promising tool for experimental psychology, enhancing the ecological validity of psychological science. The advantage of VR is that it enables researchers to study emotional and cognitive processes under realistic conditions while maintaining strict experimental control. To make it easier for scientists to get into the world of VR research and to improve the comparability of scientific results, we have created and validated a standardized set of 3D/360° videos and photos. Study 1 investigated the electrophysiological differences between motivational and emotional reactions exhibited under immersive VR and conventional 2D conditions. The obtained frontal alpha asymmetries show diverge patterns between the two conditions giving rise to further speculations that associated psychological processes exhibit more natural functional properties under immersive conditions. The feeling of being at the center of a realistic VR environment creates a sense of self-relevance. In VR, motivational tendencies and emotional reactions are related to objects or persons within the vicinity of the participant and not to the stimuli presented on a screen. Study 2, investigating the memory performance for VR videos as opposed to a conventional 2D screen presentation, provides evidence that memory formed under immersive conditions created more profound memory traces. This so-called memory superiority effect for the VR conditions might again result from the feeling of being in a scene, thus facilitating the formation of autobiographical memory. The implementation of VR experiments using the database is straightforward as it does neither require much technical equipment nor a high level of VR expertise.

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Library for universal virtual reality experiments (luVRe): A standardized immersive 3D/360° picture and video database for VR based research

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Abstract
Virtual reality is a promising tool for experimental psychology, enhancing the ecological validity of psychological science. The advantage of VR is that it enables researchers to study emotional and cognitive processes under realistic conditions while maintaining strict experimental control. To make it easier for scientists to get into the world of VR research and to improve the comparability of scientific results, we have created and validated a standardized set of 3D/360° videos and photos. Study 1 investigated the electrophysiological differences between motivational and emotional reactions exhibited under immersive VR and conventional 2D conditions. The obtained frontal alpha asymmetries show diverge patterns between the two conditions giving rise to further speculations that associated psychological processes exhibit more natural functional properties under immersive conditions. The feeling of being at the center of a realistic VR environment creates a sense of self-relevance. In VR, motivational tendencies and emotional reactions are related to objects or persons within the vicinity of the participant and not to the stimuli presented on a screen. Study 2, investigating the memory performance for VR videos as opposed to a conventional 2D screen presentation, provides evidence that memory formed under immersive conditions created more profound memory traces. This so-called memory superiority effect for the VR conditions might again result from the feeling of being in a scene, thus facilitating the formation of autobiographical memory. The implementation of VR experiments using the database is straightforward as it does neither require much technical equipment nor a high level of VR expertise.

Keywords Virtual reality · Data Base · Electroencephalography · Frontal alpha asymmetries · Memory · Video

Introduction

In the last few years, Virtual Reality (VR) has undergone incredible technological advancements and is becoming increasingly accessible to a growing audience through easier handling. It thus has also found its way into experimental psychology, being a valuable tool to study basic cognitive and emotional processes under realistic conditions (for an overview, see Cipresso et al., 2018). Foremost, the application of VR might improve the ecological validity of psychological science as it enables researchers to study aforementioned processes under multimodal and complex conditions typical to real-life situations while maintaining strict experimental control (Parsons, 2015; Smith, 2019).

Emotional and cognitive processes have developed over millions of years (Darwin & Bynum, 2009) in a complex environment and are specifically adapted to it. Notwithstanding, experimental psychology has over the last decades predominantly reduced the investigation of said processes to a rudimentary laboratory environment; however, for well-founded reasons. The maxim of experimental control makes it possible in the first place to isolate distinct psychological processes and to identify their neural correlates and substrates. Nevertheless, science claims to unravel the processes underlying complex naturalistic events. To grasp prominent aspects of the reality-related psychological functioning, aside from picture stimuli, videos are often used. They capture defining aspects of real-life experiences, including a multimodal stream of information, dynamically evolving and varying over time (Samide et al., 2019).

Although psychological science went to great lengths to recreate authentic experiences within the laboratory, especially the induction of emotion within the laboratory is at odds

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with how they are induced in real-life. In particular, a further concern originating from the conventional mode of presentation is that it relies on participants recalling or reliving emotional memories in order to induce affect (Harmon-Jones, 2019) rather than the situation itself triggering emotions. Emotions and affect serve as information for cognitive heuristics applied in the making of judgments (Schwarz, 2000). However, the informative value of images presented on a computer screen does not convey current environmental information. Instead, it serves as a reminder to a previously perceived emotion. For example, seeing a picture of a person standing on a cliff might trigger memories and/or feelings associated with fear of heights. Such retrieved emotions have another informative value than those proprietary to the situation: Watching a horror movie as well as actually being in an abandoned house elicits fear. However, in contrast to the real-life situation, movie-induced fear does not inform cognition by promoting corresponding flight behavior (other than turning off the TV) and can even be entertaining. Although both types of fear are overlapping concepts, they exhibit unique features of which some cannot be studied within conventional laboratory setups. The unmitigated nature of an *experience* (multimodal conscious representation) is what makes the distinction from merely *seeing* (two-dimensional visual impression*)* a stimulus (Kisker et al., 2020).

Virtual reality has shown that it promotes realistic behavior (Kisker et al., 2019a) informed by appropriate emotional reactions that are triggered by, and adapted to the environment itself. As VR users are shielded against all sensory input other than the virtual environment with a head-mounted display (HMD), an immersive experience is created (Felnhofer et al., 2015; Slater & Wilbur, 1997). This further facilitates a strong feeling of being physically present in the scene, commonly referred to as *the sense of presence* (Nilsson et al., 2016; Slater & Wilbur, 1997). Consequently, emotional reactions are adapted to the entire VR environment and not to a stimulus presented on a screen in an otherwise neutral laboratory environment.

Immersive experiences do not only modulate emotional processes (Diemer et al., 2015; Gorini et al., 2010), they also impact cognitive processes, including memory (Schöne et al., 2019; Smith, 2019) and attention (Iriarte et al., 2012; Urech et al., 2015). A recent publication replicated Simons' and Chabris' *Invisible Gorilla paradigm* in VR (Schöne et al., 2020). While under conventional conditions about 70% of the participants missed the Gorilla, the effect was diminished to 30% in the VR condition using the very same video material. Although the effect was not completely attenuated, sustained inattentional blindness plays a much smaller role under realistic conditions than derived from classical laboratory settings. The attentional processes might be modulated by physical vicinity and/or self-relevance.

The latter seems to be one of the most prominent features of VR (Schöne et al., 2020), almost inevitably resulting from immersion and presence, and should generally be further considered and systematically manipulated (Samide et al., 2019). VR experiments easily allow for that kind of manipulation. For example, being the victim in a VR scene of domestic violence as opposed to being a passive bystander enhances the sensation of fear, helplessness, and vulnerability (Gonzalez-Liencres et al., 2020). Most importantly, a first-person perspective, that is, being subject of a scene, leads to taking the scene personally and is associated with elevated behavioral and physiological reactions. Notably, the simulation of immediate physical danger evokes appropriate behavioral and cognitive coping strategies even if the situation is fantasy-based, for example, a zombie attack. Hence, the brain emits danger signals that trigger reactions appropriate to a real situation (Lin, 2017). Under conventional laboratory conditions, self-relevance can often only be achieved indirectly, for example by associating stimuli with an external monetary reward (Deci, 1971) or aversive sound (Riesel et al., 2012).

Creating Virtual Environments

To the best of our knowledge, no coherent VR database (i. e., material of one type and source) is available, which means that researchers have to create VR environments individually. The creation of the material is time-consuming and requires a high degree of expertise and capabilities. Furthermore, the creation of individual VR settings might lead to the use of stimuli that are not compatible in terms of realism, presence, and hence the emotions they elicit. It is therefore of utmost importance for researchers to select appropriate and foremost controlled stimuli for inducing a specific emotional state when investigating emotions and cognitive processes (Marchewka et al., 2014).

In principle, VR environments can be created in two different ways: Computer-generated environments are constructed with game engines like *Unity* or *Unreal*. Their major advantage is the absolute creative freedom and versatility, as anything imaginable can be simulated in VR. Using additional hardware, those environments potentially incorporate real-life interaction (e.g. hand tracking). However, creating a realistic and responsive environment requires a high level of technical skills, a hurdle that does not need to be overcome using VR cameras. VR cameras record the whole surrounding environment (360°/panoramic), more advanced models even in 3D (3D/360°). 3D/360°-VR videos can be experienced, just like computer-generated environments, through head-mounted displays (HMDs). Therefore, VR-videos are an easy to use and cost-efficient way to enter immersive virtual environments. Although the interaction within VR videos is mostly limited to tracking and translation of the head-movements, the translated head tilts and shifts resemble real-life exploration of a real environment. In particular, 3D/360° videos create the impression that objects, people or animals can be touched or might touch the observer in return. Those experiences come with a high sense of presence (Breves & Heber, 2020; Chirico et al., 2018; Rupp et al., 2019). The photorealism and naturalistic character of these videos give rise to realistic behavior (see also Higuera-Trujillo et al., 2017).

Library for Universal Virtual Reality Experiments – luVRe

Up to the present day, we recorded 450 videos with 69 themes using an Insta 360° VR camera (Insta360, Shenzhen, China). Each theme comprises several videos, varying greatly in part. For example, eleven videos of various animals are assigned to the theme zoo. The database contains 3D/360° videos with a length of 30s seconds (plus extended versions in some cases) with 4 K resolution and 60fps as well as 3D/360° pictures with 8 K resolution when feasible. To avoid motion sickness, most videos are recorded using a tripod. We have estimated a standard body height of 175 cm and a corresponding lens height of 163 cm. Preliminary tests determined no perceived height incongruencies when people were larger or smaller than our standard lens height or even sitting (see also Rothe et al., 2018).

Paralleling previous databases (Bradley et al., 2001; Dan-Glauser & Scherer, 2011; Li et al., 2017), luVRe comprises everyday life scenes as well as extraordinary encounters with varying arousal and valence. Among them, there are calming natures scenes (jetty by a lake, beach, forest), neutral scenes (hotel rooms, farm), tourist attractions/cities (Amsterdam, New York, London, Hamburg, Vienna) and interesting places (restaurants, museums, decommissioned Soviet submarine). Most importantly, the database contains stimuli aiming at eliciting strong emotional and motivational reactions to enable researchers to study the dynamic unfolding of complex affective reactions under realistic conditions. We filmed rather aversive scenes, like visiting a dentist, impressions from an emergency room, during an alarm in an atomic shelter, at a funeral parlor, during surgery, and a police training for a hostage situation. To cover a broad spectrum of emotional reactions, we also included highly appetitive scenes like male strippers, show cooking, playing puppies, or getting a beer at a bar.

Current Studies and Hypotheses

The aim of this publication is to provide evidence that an application of 3D-VR videos is a valuable tool for psychological science. To this end, we investigated the emotional/motivational and cognitive processes associated with immersive VR experiences as opposed to conventional laboratory setups. Specifically, we present the very same stimulus material in both domains in order to identify the mechanism that is uniquely associated with either one of them. Study No. 1 investigates the electrophysiological correlates of approach and withdrawal motivation by means of frontal alpha asymmetries (FAAs). We hypothesized that the unmediated experiences of VR would facilitate a categorical shift in motivational processing resembling real-life processes. Study No. 2 investigates the depth of mnemonic processes in relation to the immersiveness under which the memory trace is formed. Under still unknown conditions, VR experiences seem to propagate the formation of autobiographical memories (see 'Study 2'). Those memories are retrieved with greater accuracy constituting the VR memory superiority effect. We hypothesized that higher retrieval rates for VR experiences, as opposed to a conventional laboratory setting, would result from real-life mnemonic processing of luVRe videos. Replicating this prominent effect in VR thus is a benchmark for the legitimacy of luVRe and the applied experimental design.

Considering the size of the database and the psychophysical exertion that longer VR sessions impose on a participant, only a representative sample of luVRe was subject to testing in both studies. Furthermore, to ensure that the participants experience the virtual simulation as they would under real-life conditions, a dedicated experimental task was omitted.

Study 1: Frontal Alpha Asymmetries in Virtual Environments

Conventional experimental setups investigating emotional and motivational processes in response to pictorial stimuli oftentimes require participants to rate stimuli subsequent to their presentation (Bradley et al., 2001). Although this well-established approach might be suitable for the 2D picture presentation, we hypothesized it would not fully capture the immersive effect of VR. Two commonly used approaches to 2D scene rating seem applicable: Either stimulus and rating scene are simultaneously presented on one screen, or the rating occurs subsequent to the stimulus presentation. Technically spoken, both methods can and were partly used in VR paradigms (Li et al., 2017), but they present some inherent constraints to the paradigm. A rating overlay superimposed on the scene potentially reliably measures affect exactly when it occurs, but would be at odds with the goal of VR research to create a sensory impression mimicking real-life experiences. Alternatively, a subsequent rating in a neutral VR space would be feasible. However, the participant would perceive a complete change of scenery between stimulus exposure and rating, while the standard setup would take place within the same temporal-spatial reference frame. This approach neglects both, the nature of a 2D compared to a 3D experimental setup, and the meaning conveyed by the stimuli within such a frame. For example, the image of an attacking animal does not pose a threat, but is a token for a similar real-life experience (see introduction). Accordingly, motivational and emotional reactions to pictorial stimuli can depend heavily on the individuals' experiences and might be weak, as pictoral stimuli alone sometimes do no suffice to elicit appropriate emotional tendencies (Harmon-Jones & Gable, 2018). Conversely, the immersive nature of VR leads to an entirely different experience for the participant. Although it can be assumed that participants in VR are aware that they are experiencing a sophisticated simulation (Kisker et al., 2019a; Lin, 2017), a rating of a VR scene is indeed a rating of an experience and not a token (Kisker et al., 2020).

Consequently, real-time measurements of affective processing in response to stimulus exposure might provide more meaningful insights into the effects of immersiveness on motivation and emotion. The experimental approach of study No.1 leverages the affordances of immersive VR experiences. Foremost, the three-dimensionality of VR constitutes the feeling of presence in, and self-relevance of the virtual environment and events. Moreover, given that VR promotes stronger emotional reactions than 2D setups (e. g. Gorini et al., 2010) and based on pilot studies,[1] we hypothesized that presence, physicality (3D; see Kisker et al., 2019a), and emotional immediacy facilitate strong motivational tendencies surfacing on an electrophysiological level.

Motivation and affect are intrinsically intertwined. Organisms tend to approach rewards and to perform beneficial operations that fulfill their needs or achieve positive goals. Conversely, they withdraw from any undesired outcome or punishment (for a most recent review, see Harmon-Jones, 2019; Harmon-Jones & Gable, 2018). These motivational tendencies are reflected on an electrophysiological level by alpha-band oscillations (8–13 Hz) measured over frontal scalp areas, called frontal alpha-asymmetries (FAAs). Specifically, the relative difference of alpha power at left-hemispheric and homologues right-hemispheric electrodes is believed to either reflect approach motivation (relative reduction over left areas) or withdrawal motivation (relative reduction over right areas). However, aside from this motivational model, other processes have been associated with two further models. The confundation of affect and motivational processes initially spawned a model associating a relative left-sided reduction of alpha power not with approach motivation, but with positive affect and a relative right-sided asymmetry not with withdrawal, but negative affect (Harmon-Jones & Gable, 2018). This valence model of frontal alpha-asymmetries (Davidson & Fox, 1982), however, does not account for the fact that anger, as an emotion we would consider to be of negative value, also leads to a relative left-sided reduction of alpha power. Relating motivational directions to FAAs, however, also does not seem to provide a final conclusion as evidence highlighting the role of cognitive control on affect emerges. Even neutral stimuli can elicit equally strong FAAs as high-approach positive pictures (erotic pictures), implying that the alpha asymmetry dynamics might actually mirror top-down inhibitory executive processes regulating the generation of affect (Schöne et al., 2016). Hewig (2018) further argues that FAAs might reflect intention consisting of a cognitive component, that is, the mental representation of the intended effect, and an affective-motivational component, the feeling of being determined to act. Most recent research implies that engaging in effortful control of emotion also accounts for the generation of FAAs (Lacey et al., 2020). Taken together, FAAs seem to be a meaningful starting point for real-time exploration of the dynamic interplay between affect, motivation, and executive control in a real-life environment and thus, for conceptually validating immersive VR videos as a suitable tool. Due to the explorative nature of the experiment, no dedicated hypothesis was defined. Rather, the aim was to identify and explore meaningful differences between VR and 2D presentation on the item level. The novelty of the method and the resulting limited publication base complicate the prediction of whether and what specific differences might occur. Aforementioned evidence is obtained under laboratory conditions. Hence, to which extent it might translate to immersive VR conditions is unclear. However, when the FAAs do not differ significantly between conditions, it can be concluded that the cognitive and emotional mechanisms deployed in both conditions are very much alike and that VR does not exhibit unique features other than a conventional computer. In contrast, different FFAs for both conditions would make a case for VR as a tool, as it could be concluded that the immersiveness of VR would give rise to more realistic cognitive and emotional functioning.

Methods Study 1

Participants

Forty-one students from Osnabrück University gave informed consent and participated in exchange for 15€ or partial course credits in the study. All participants were screened for psychological, neurological and cardiovascular disorders. They had normal or corrected-to-normal sight; in the latter case, only

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[1] We repeatedly observed that VR users tried to pet animals, looked behind corners, did a small backward jerk whenever something unpleasant entered the scene or raised their arms for self-defense.

people with contact lenses were admitted. One participant was excluded during anamnesis due to the intake of centrally nervous effective medication. Two further participants were excluded from the analysis as they experienced the *screen door effect* (SDE), a visual artifact letting the viewer see distinct pixels or lines. The SDE limits immersion, as it reduces visual quality (Cho et al., 2017). Thus, a sample size of $n = 19$ remained per group (3D/360° group: *M*age = 21.26, *SD*age = 2.54, 15 female, 17 right-handed; 2D group: *M*age = 23.26, *SD*age = 2.60, 15 female, 14 right-handed). The study was conducted in accordance with the Declaration of Helsinki and has been approved by the local Ethics Committee of Osnabrück University.

Stimulus Material

Fifteen exemplary videos from the *Library for Universal Virtual Reality Experiments (luVRe)* were selected on the basis of their affective value. The classification of stimuli was based upon Lang and Bradley's (2010) description of appetitive and aversive stimuli: Stimuli related to nutrition, reproduction, joy, and caregiving were classified as positive. Stimuli that posed threats, like kidnapping and emergency room scenes, were classified as negative. Stimuli were classified as neutral if they did not contain any special events or (inter-)actions, such as the exterior view on plain buildings and empty rooms (see Fig. 1 for examples). Since we could not rely on preliminary affective ratings, the videos were assigned to the respective affective dimension when the project members agreed on the emotional reaction to be expected (see Figs. 1, 2 and Table 1).

Each video was 60 s long. Twenty randomized sequences of the 15 videos were generated, subject to the constraint that no more than two videos of the same valence follow each other in presentation (Bradley et al., 2001).

Procedure

Both, 3D/360° videos and 2D videos were presented using the *HTC Vive* VR system to control for possible confounding factors that could result from wearing the VR system, like electromagnetic inferences or physical pressure on the electrodes (see Fig. 3). For the 3D/360° condition, the videos were presented as fully immersive VR-3D/360° videos. In order to create a similar experience in the 2D condition, only deprived of the immersive three-dimensional nature of VR, the videos were projected onto a large frameless virtual screen within the VR environment. Thus, the proportions of the depicted objects on the retina were maintained, and peripheral vision was stimulated likewise. However, the presentation for one group was as VR-3D/360° video, and the other group viewed videos in 2D albeit wearing an HMD. Each of the 20 video sequences was presented to one participant. The participants were allowed to make slight horizontal and vertical head

Table 1 Content and classification of the 15 exemplary videos that were used as stimuli from luVRe

Neutral	
Bath Room	A clean, simple hotel bathroom.
Car dealer	Showroom of a car dealer, new cars are all over the room.
Elbtunnel	Long, narrow tunnel in Hamburg. A cyclist passes by.
Hotel Room	Hotel room which is empty except for furniture.
Planetarium	Exterior view on the planetarium building in Hamburg.
Negative	
Bloody bathroom	Bathroom with bloodied walls, an axe, and pieces of meat lying nearby. Quiet humming and shaking at the door handle can be heard.
Kidnapping	Jogger gets kidnapped under a dark bridge by a man wearing a mask.
Emergency Room	Two caregivers ventilate and treat one patient. No blood or injuries are visible.
Dentist	Sitting on a dentist's chair, watching a dentist handling the drill.
Bunker	Bunker with flickering lights. After a few seconds, an alarm sound, a door opens, and a person in an ABC suit crosses the room.
Positive	
Rhinoceroses	Three rhinoceroses in the enclosure, eating and fixing one. Zebras come running in and chase away the rhinoceroses. The rhinoceroses run close by.
Bar	Sitting at a bar with other people drinking. The waiter serves beer.
Lake	View from a footbridge over a wide lake. At the edge of the scene are trees by the water.
Horses	Two horses, very close by, nudging and inspecting one.
Show Cooking	View of an open kitchen where a cook prepares food.

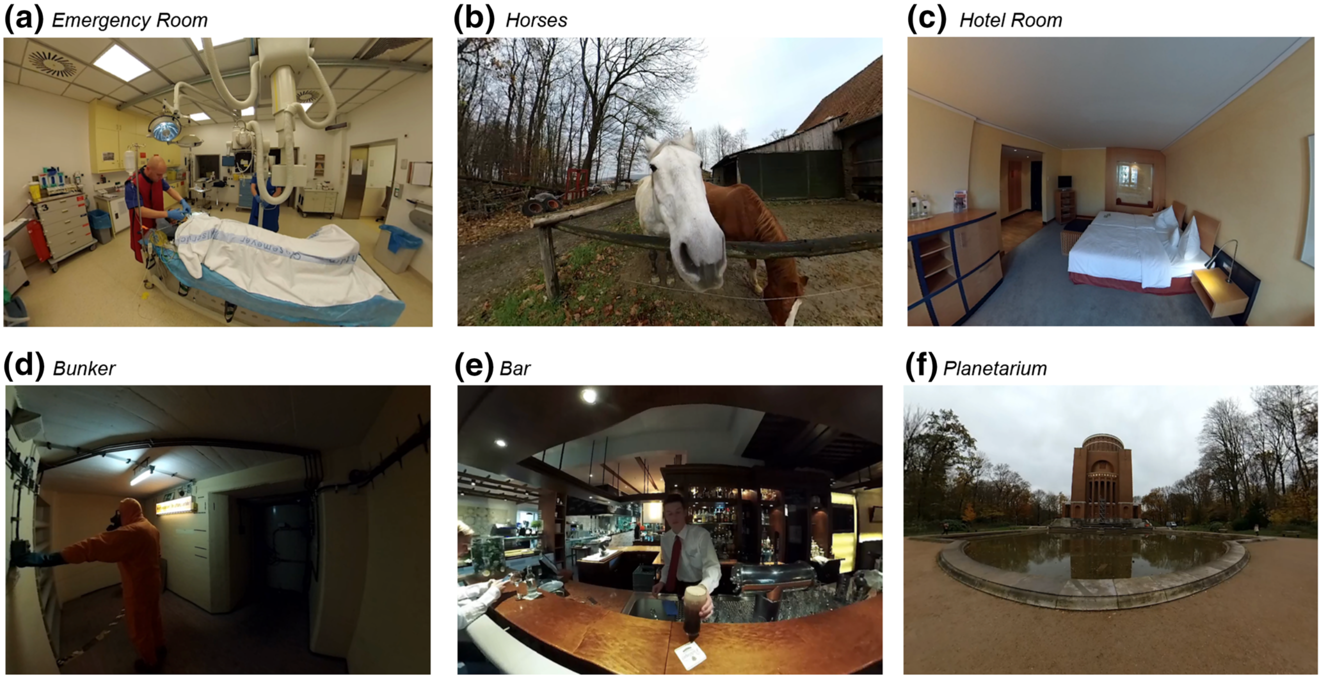

Fig. 1 Exemplary stimuli. *Note.* Screenshots are taken from six of the 15 videos used as stimulus material, depicting the *Emergency Room* video (**a**), the *Horses* video (**b**), the *Hotel Room* video (**c**), the *Bunker* video (**d**), the *Bar* video (**e**), and the *Planetarium* video (**f**). The slightly distorted display of the screenshots results from being captured with a conventional video player instead of a 360° compatible program. During the experiment, the videos were displayed without distortion

movements to explore the scene but were encouraged not to do so too intensely or abruptly.

To accommodate the VR session prior to the experiment, especially to the HMD, participants spent 60 s in a neutral virtual room, followed by a visual ten seconds countdown announcing that the experiment was about to begin. The total presentation time for the 15 trials was approximately 22 min. Each trial started with a 20 s resting phase in the plain room with white walls, followed by a one-second fixation (red cross appears on the white wall). Then, one of the fifteen videos was presented for 60 s (see Fig. 2).

Subjective Measures

After the video presentation, the sense of presence was measured using the German version of the *Igroup Presence Questionnaire* (IPQ; Schubert et al., 2001), and participants were asked about prior VR experiences and motion sickness during and after the experiment.

Electrophysiological Recording and Preprocessing

During the presentation of the 15 trials, an electroencephalogram (EEG) with 128 electrodes was recorded, attached in

Fig. 2 Timing of a trial. *Note.* Each trial started with a 20 s resting phase, followed by a one-second fixation. Each video was presented for 60 s. Each trial took 81 s. The slightly distorted display of the screenshots results from being captured with a conventional video player instead of a 360° compatible program. During the experiment, the videos were displayed without distortion

Fig. 3 Combination of VR HMD and EEG. *Note.* The VR equipment included the immersive *HTC Vive* HMD, headphones for stereoscopic sound, and the *HTC Vive* tracking stations for real-time head-tracking. The VR equipment was carefully arranged atop the 128-electrode EEG

accordance with the international 10–20-system. The ActiveTwo amplifier system from BioSemi (Amsterdam, Netherlands) was used. The sampling rate was 512 Hz, the bandwidth (3 dB) 104 Hz. Additionally, a horizontal electrooculogram (hEOG) and a vertical electrooculogram (vEOG) were recorded, and a common mode sense (CMS) and a driven right leg (DRL) electrode were applied. The EEG was recorded on the investigators' computer using ActiView702 Lores.

The data processing followed the recommended standard procedure for FAA-analysis (see Lacey et al., 2020; Smith et al., 2017): The data were segmented into epochs from -1 s to 60s, relative to the onset of each video. Afterward, the EEG data was baseline corrected (500 ms before stimulus onset) and filtered between 0.1 Hz and 24 Hz. The chosen low-pass filter of 24 Hz prohibits interference from the 50/60 Hz mains power. Each electrode was detrended separately. The data was squared and logarithmized. A window size of one second was defined and shifted with a step size of 0.1 s. A Hamming window was applied, and the fast Fourier transformation (FFT) was calculated. The alpha band of 8 Hz to 12 Hz was extracted. Due to the robustness of this methodological approach, neither was a trial excluded from further analysis nor was any data omitted. For each video, a grand mean including all participants of the same group was calculated and averaged over selected time windows (see below: statistical analysis). For the calculation of the frontal alpha asymmetry score (FAA-score), electrode F4 was subtracted from electrode F3 (logarithmized left alpha power minus logarithmized right alpha power).

Statistical Analysis

Questionnaires Prior VR experience and experience of motion sickness were recorded as categorical variables and analyzed using Pearson's *Chi-square* test. For the analysis of the sense of presence, the IPQ scales *General Presence, Spatial Presence, Involvement,* and *Realness* were calculated. As *General Presence* was not normally distributed ($p < 0.05$), Mann-Whitney-*U*-test was performed, and Cronbach's alpha was calculated.

EEG-Data In line with our exploratory approach, and to account for the temporal dynamics of the video material and hence the unfolding of affective processes, we identified relevant time-windows before averaging over subjects with a running t-test with the time domain. To identify the most prominent motivational differences, the FAAs of both groups were tested against each other in that manner. The approach described below was deemed necessary as significant events are unevenly distributed over the 60s timeline of each video. As a criterion for reliable significance, the shortest eligible time window subject to further analysis consisted of ten consecutive significant data points and was thus one second long (albeit the vast majority were several dozens of seconds long). For the sake of simplicity and clarity, the so selected time-windows were averaged and further analyzed by separate *t*-tests, which are reported below.

Results Study 1

Subjective Measures

Participants of both groups neither differed with respect to their prior experience with HMDs ($\chi 2(1) = 0.100$, $p = .752$) nor regarding motion sickness (during video presentation: $\chi 2(1) = 0.000$, $p = 1.0$; after video presentation: $\chi 2(1) = 1.026$, $p = .311$).

The 3D/360° group reported higher sensations of general and spatial presence (*General Presence*: $U = 117.50$, $z = -1.916$, $p = .033$, $M_{VR} = 4.47$, $M_{PC} = 3.74$; *Spatial Presence*: $U = 86.50$, $z = -2.577$, $p = .005$, $M_{VR} = 4.35$, $M_{PC} = 3.50$). However, both groups did not differ with respect to *Involvement* ($U = 170.00$, $z = -0.31$, $p = .494$, $M_{VR} = 3.80$, $M_{PC} = 3.81$) and *Realness* ($U = 135.50$, $z = -1.322$, $p = .095$, $M_{VR} = 4.18$, $M_{PC} = 3.84$). Cronbach's α was good for *Spatial Presence* ($\alpha = .794$) and *Involvement* ($\alpha = .719$), but poor for *Realness* ($\alpha = .564$). *Cronbach's* α could not be calculated for the one-item scale *General Presence*.

Dependent Measures

As expected, the FAA results of the respective videos differed considerably depending on the type of presentation (3D/360° vs. 2D). Importantly, the FAA-scores of both groups indicate opposite motivational tendencies in 14 of 15 videos. The motivational tendencies of both groups implied the same direction only for the emergency room video but still differed significantly in their intensity: In the 3D/360° group, the higher FAA-score implied a significantly stronger avoidance motivation than in the 2D group. The FAA-scores and respective statistics per video are given in Table 2 and visualized in the corresponding Fig. 4. The latency of the time windows ranged from one to 38 s ($M_{\text{latency range}} = 10.78$ s).

Table 2 Results of the t-test for independent samples comparing the mean FAA-scores of the respective time windows between both groups per video. The time window is given in seconds after stimulus onset

video	time window	*t*-test			descriptives			
		T	*df*	*p (2*-tailed*)*	$M_{3D\text{-}360}$	$SD_{3D\text{-}360}$	M_{2D}	SD_{2D}
Bloody bathroom	25–44	2.109	37	.042	−0.019	0.058	0.018	0.048
	50–54	−2.140	37	.039	0.032	0.053	−0.018	0.087
Kidnapping	23–40	2.498	37	.017	−0.027	0.049	0.023	0.071
	41–48	2.038	37	.049	0.046	0.058	−0.009	0.080
Bunker	37–55	2.107	37	.042	−0.005	0.063	0.034	0.048
Emergency room	35–37	−2.273	37	.029	0.075	0.067	0.007	0.111
	53–56	−2.185	37	.036	0.065	0.08	0.002	0.097
Dentist	16–31	2.055	37	.048	−0.004	0.062	0.037	0.059
	53–57	2.048	37	.048	−0.038	0.08	0.024	0.102
Bathroom	4–8	2.157	37	.038	−0.044	0.076	0.01	0.077
	22–28	−2.066	37	.046	0.041	0.092	−0.016	0.076
	51–58	2.384	37	.023	−0.060	0.060	−0.012	0.062
Car dealer	19–56	−2.137	37	.040	0.019	0.036	−0.005	0.031
Elbtunnel	4–40	−2.226	37	.033	0.007	0.047	−0.020	0.022
Hotel room	7–13	−2.192	37	.035	0.036	0.076	−0.015	0.064
	23–28	−2.283	37	.029	0.024	0.064	−0.024	0.063
Planetarium	39–40	2.174	37	.037	−0.036	0.075	0.029	0.105
Bar	0–31	−2.198	37	.035	0.021	0.051	−0.014	0.044
	35–36	−2.530	37	.016	0.036	0.112	−0.071	0.143
Lake	13–15	2.243	37	.031	−0.008	0.066	0.041	0.065
	25–28	−2.089	37	.044	0.025	0.041	0.004	0.088
	36–41	2.482	37	.018	−0.028	0.052	0.023	0.071
Horses	0–38	2.110	37	.042	−0.031	0.036	0.003	0.060
Show cooking	20–29	2.263	3	.030	−0.029	0.055	0.017	0.069
	43–48	2.108	37	.042	−0.041	0.092	0.022	0.090
Rhinoceroses	41–44	2.159	37	.038	−0.035	0.078	0.024	0.090

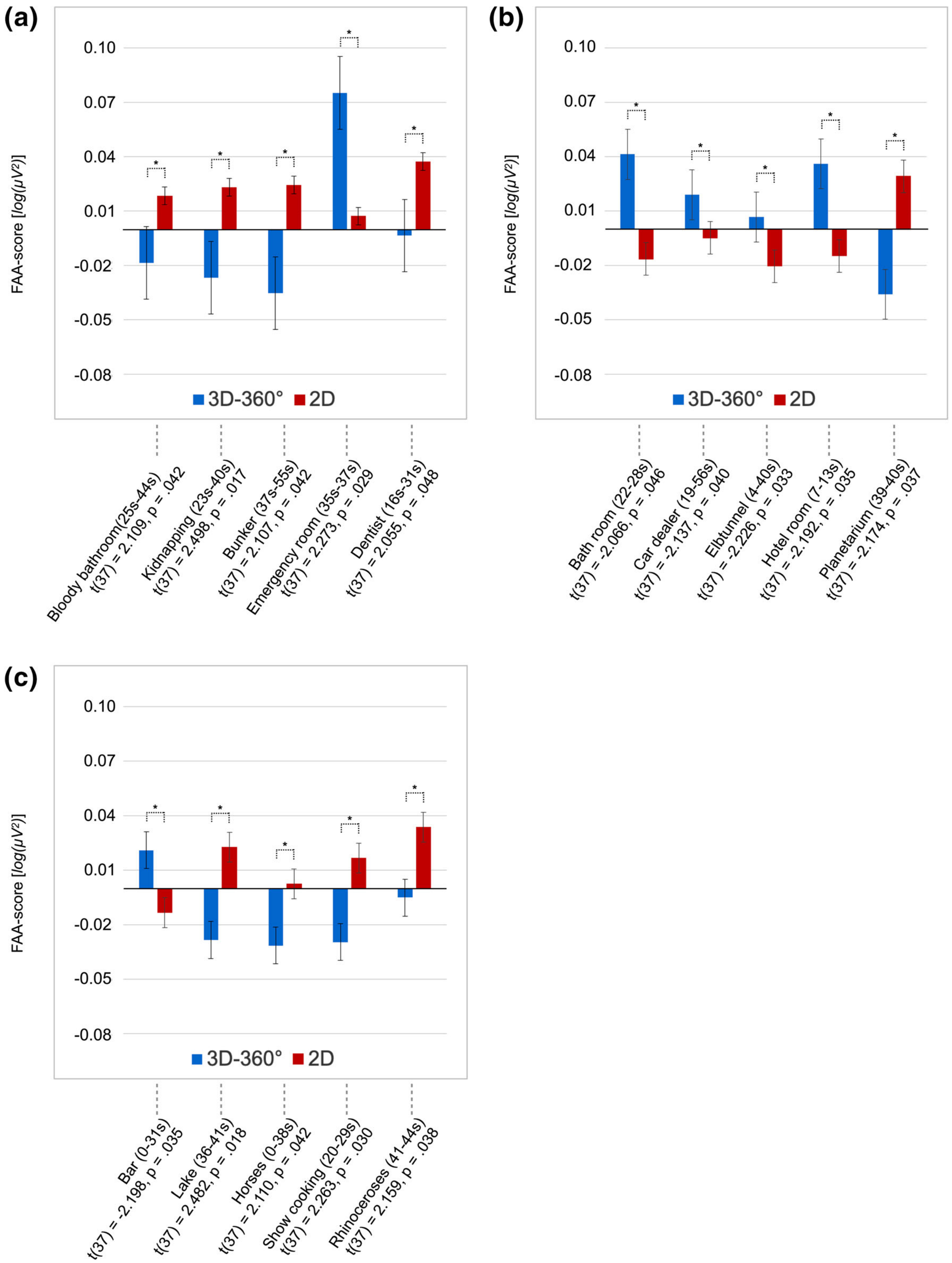

Fig. 4 FAA scores for luVRe videos. *Note*. Mean FAA-score per video for the selected time windows for significant events, grouped according to the categorization as negative (**a**), neutral (**b**), and positive (**c**). Significant events within a video included, for example, the onset of weeping (bloody bathroom video), entry of a person in an ABC suit (bunker video), serving of a beverage (bar video), and a horse nudging the viewer with his nostrils (horse video). According to conventional interpretation, positive FAA-scores reflect withdrawal motivation, whereas negative FAA-scores reflect approach motivation. Significant differences between both groups are marked (* $p < .05$). The error bars depict the standard error of the mean

Discussion Study 1

The aim of study No. 1 was to assess the emotional and motivational responses to videos from *luVRe* under immersive VR conditions as compared to a more conventional 2D condition. Noteworthy, the VR-videos did not cause considerably more motion sickness as compared to the 2D presentation. Most importantly, the 3D/360° group reported a higher sense of general as well as spatial presence. Hence, watching a video through an HMD does not lead to an enhanced feeling of being in the scene per se. Rather, the three-dimensionality is to be considered the decisive factor. Being surrounded by a 3D/360° environment shields against any external sensory input beyond the virtual environment and thus, underlies immersion and presence (e.g., Slater & Wilbur, 1997). It is noteworthy that this shielding effect does not result from physically blocking any external visual and acoustic cues by means of an HMD, but by the physicality of the presented environment. What might further contribute to a strong feeling of presence is that processing 3D environments is the brain's natural mode of operation. Although it could be assumed that the reduced sensory impressions facilitate processing, both simple and complex tasks lead to higher cognitive load under 2D conditions as compared to 3D conditions (Dan & Reiner, 2017). From the point of view of evolutionary psychology, the brain has evolved in a complex environment and thus is adapted to process the environment in which the organism is physically present. This more realistic processing style could situate the participants in the VR environment and thus, constitutes presence. The fact that involvement and realness were equally high can be attributed to the fact that we employed a passive viewing paradigm with photorealistic stimuli.

The FAA results shed new light on emotional and motivational processes as well as their regulation in realistic as opposed to conventional environments. For the sake of clarity, we would like to emphasize that we are not predominantly interested in investigating FAAs per se, but in assessing differences in processing style between VR and conventional laboratory conditions (see introduction). Our intention was to provide a methodological and factual starting point for further in-depth research along with an impulse to reconsider prevailing theories. To give a complete account of the observed effects is not within the scope of the paper. That being said, it is evident that the way the same stimulus material is processed fundamentally differs between both conditions, most strikingly for videos previously categorized as negative. Thus, the following discussion will focus on these stimuli in order to exemplify some core concepts and ideas about the benefits of VR applications in this field of scientific research.

All negative videos in the 2D condition elicit a FAA that would be considered to index a tendency to withdrawal or negative affect, whereas 4 out of 5 FAAs in the 3D condition go into the other direction. In the emergency room scene, depicting reanimation, the withdrawal motivation in 3D is more pronounced compared to the 2D condition. The opposite pattern is the case for the dentist scene: Participants exhibit a strong withdrawal tendency when the dental drill starts spinning for the 2D group, compared to a small to neutral approach tendency for the 3D group. Explanations of this behavior are rather speculative but continue to spin the threat of the latest theories. The emergency scene might be interesting to watch in 2D when being outside the spatio-temporal reference frame. However, in a VR environment, the participant stands next to a scene where two medical workers are trying to reanimate a person and is ultimately confronted with real death, which, for example, strikes fear. Promoting the firm belief of being within the spatio-temporal reference frame of the scene, VR experiences reduce both physical and mental shielding from the occurring events. Thus, the meta-awareness that the virtual environment cannot affect one or be affected in return diminishes (Kisker et al., 2019b; Pan & Hamilton, 2018). Consequently, events within the virtual environment and their implications become highly self-relevant as they immediately affect the user, altering emotional and motivational responses as compared to mere on-screen experiences (Kisker et al., 2019b; Schöne et al., 2019).

Whereas emotion seems to be the dominating topic in this scene, emotion regulation could play an essential role in the dentist scene: Being reminded of a visit to the dentist, as in the 2D condition, leads to avoidance of negative affect; moreover, the visit itself is not associated with pleasantness. However, to get over with such a real-life visit, withdrawal motivation has been sufficiently downregulated or suppressed. FAAs in the 3D condition thus might be subject to or reflect regulation and intention (Hewig, 2018; Lacey et al., 2020).

This example, in particular and together with the other results from the negative category, shows the importance of realistic stimuli. They facilitate the investigation of real-world cognition and illustrate the conceptual differences between presenting stimulus material as a 2D reminder as opposed to a virtual experience. In contrast to the 2D group, the 3D group reacts to all other negative stimuli with approach and positive affect – according to the FAA. Despite the negative scene, participants might build the intention to flee from the atomic shelter or to fight the attacker in the kidnapping scene. Basically, this argumentation follows the idea of Harmon-Jones and Allen's seminal study (1998), showing that anger as a negative emotion can lead to an approach-related FAA. Our study shows that under realistic conditions, similar results can be obtained, and, most importantly, scientific concepts about emotion, motivation and their regulation can be extended and suited to a more complex and realistic image of emotional experiences.

To summarize, the VR condition yielded completely different results as the current conventional laboratory condition, indicating that conventional paradigms do not translate into the virtual domain without loss. That can mainly be attributed to the VR environment providing a believable environment to which the motivational and emotional reactions are adapted. The immersiveness of VR constitutes a feeling of being in the scene; the impression of an explorable and touchable environment facilitates different processes as opposed to conventional laboratory conditions. The apparent deviation from laboratory results calls for a further in-depth investigation of said processes in order to draw a more appropriate picture of realistic cognitive and emotional mechanisms.

Study 2. Remembering Virtual Experiences

Among the versatile applications of VR as a tool in psychological research, memory research could particularly benefit from it. Conventionally, memory studies employ a design that resembles rather a cue-indexing approach than investigating a fully-grown memory: Participants are presented with pictorial stimuli on a computer, commonly dozens of unrelated items, and have to recall them in the course of the experiment. While this and related methods serve the purpose of identifying the core mechanism of memory, they do not grasp the complex nature of real-life memory traces. Memory traces are multimodal constructs. They incorporate a scene or broader context (Barrett & Kensinger, 2010) with an event together with sensorimotor information (Kelly et al., 2007; Wilson, 2001) and emotional connotations (Erk et al., 2003; Paulmann & Pell, 2011). Our very functioning depends on recalling past events along with their spatial and temporal context (Conway, 2005; Conway et al., 2004; Greenwald, 1980; Schöne et al., 2018) as well as on creating semantic abstractions of oneself in a particular scene constituting autobiographical memory and personal semantics (Klein & Loftus, 1993). Approaches putting autobiographical aspects of memory at the center of the scientific work pay tribute to this fact (e.g., Cabeza et al., 2004; Daselaar et al., 2008; Greenberg et al., 2005; McDermott et al., 2009).

Going one step further, VR enables all kinds of memory researchers to not only passively present stimulus material but to fathom the integration of sensorimotor and memory functions under or close to real-life conditions (Kelly et al., 2007; Schultheis & Rizzo, 2001). In particular, VR allows studying all aspects of memory traces with unprecedented sensitivity and accuracy. Terms as “contextual information” and “object” in VR actually refer to a complex spatial reference frame and a three-dimensional object within. The egocentric perspective along with a feeling of presence add to the sensorimotor stream and, as outlined in the first study, to affective content. The result is an associative engram resembling the key features of real-life mnemonic structures and functioning (Kisker et al., 2019b; Schöne et al., 2019).

Current VR studies focus on objects, meaning that participants are asked to recall objects they previously encountered in a virtual environment (Kisker et al., 2019b; Krokos et al., 2019; Ouellet et al., 2018; Sauzéon et al., 2012). Previous studies on memory in VR have found an enhanced retrieval rate under more realistic conditions (Ernstsen et al., 2019; Harman et al., 2017; Krokos et al., 2019; Schöne et al., 2019; Smith, 2019), although it should be noted the effect does not always occur (Kisker et al., 2019b; LaFortune & Macuga, 2016; Lorenz et al., 2018). That is remarkable as the vividness of VR should unanimously amplify the relevance of information extracted from the surroundings. This seems to especially hold true as the feeling of being in the scene creates self-relevance (see study 1). Interestingly, exogenous self-relevant information is preferably processed (Schöne et al., 2018) and as part of the autobiographical memory reliably accessed and retrieved, which may explain the enhanced memory effect for VR stimuli. A standardized dataset might thus help to shed light on the differences in mnemonic processing of the multimodal stream of exogenous and endogenous information.

The current study aimed to replicate the memory superiority effect for VR stimuli from the luVRe-database as opposed to a conventional 2D presentation in order to validate them. To that end, we selected a set of thirty videos from luVRe we deemed to be interesting, partially overlapping with the first study. Decisive for the design were the standards of conventional mnemonic experiments, namely randomized presentation of stimulus material and subsequent recall (Sauzéon et al., 2012). We thus employed a paradigm in which the participant watched videos in a randomized order on a monitor as in any other video study as opposed to the same stimuli material in a VR condition. To the best of our knowledge, this is one of the first VR memory studies (see also Kisker et al., 2020) presenting a high number of multifaceted scene stimuli in one experiment.

The rationale behind this conservative approach was that the conventional 2D condition should replicate conventional memory effects to its best, providing a benchmark for the effects under immersive conditions. We investigated the free recall of a scene as well as details by means of cued recall. In case that the VR setup would outperform the conventional 2D setup figuratively speaking on its own ground, the study would make a case for a memory superiority effect under controlled VR conditions and not only in a single immersive VR environment as often used in VR memory studies (see, e.g., Ouellet et al., 2018).

Methods Study 2

Participants

Sixty-eight participants were recruited from Osnabrück University. The study was conducted in accordance with the

Helsinki Declaration and approved by the local ethics committee of Osnabrück University. Participants gave their informed written consent and were screened for psychological and neurological disorders. All had normal or corrected-to-normal vision. The participants were randomly assigned either to the VR condition (3D/360° videos) or to the conventional PC condition (PC, 2D-360° videos). Eight participants were excluded from the analysis due to incorrect procedures or technical problems during stimulus presentation. A sample size of $N = 60$ remained (VR: $n_{\mathrm{VR}} = 30$, $M_{\mathrm{age}} = 22.63$, $SD_{\mathrm{age}} = 2.79$, 23 female, 26 right-handed; PC: $n_{\mathrm{PC}} = 30$, $M_{\mathrm{age}} = 20.77$, $SD_{\mathrm{age}} = 1.65$, 25 female, 29 right-handed). Participants received partial course credits.

Stimuli and Procedure

Thirty 3D/360° videos from the *Library for Universal Virtual Reality Experiments* (luVRe) were used as stimuli. Each video was presented for ten seconds, resulting in a total presentation time of five minutes. Each participant saw all of the thirty videos but in different orders: To avoid position and sequence effects, five randomized orders of the thirty videos were generated.

Participants of the VR condition wore an *HTC Vive* head-mounted display (HMD), which allows for a 3D/360° view, head-tracking, and stereoscopic sound. Participants of the PC condition were seated in front of a 24″ monitor at 80 cm distance (visual angle: $2 \times 18.33°$). They could look around the video using the arrow keys. For both conditions, a basic video (cf. planetarium video, study 1), which was not part of the stimuli set, was presented to ensure sharp sight and to become familiar with looking around in the video either with the headset or the arrow keys. All subjects wore headphones for sound.

Immediately after the video presentation, the sense of presence was measured using the German version of the *Igroup presence questionnaire* (IPQ, Schubert et al., 2001), followed by a modified Taylor complex figure test (Taylor, 1969) as a distraction task. Afterward, an unannounced memory test was performed: Participants were asked to freely recall the video scenes they had seen and name them by key features (free recall, e.g., "I remember standing on a motorway bridge", cf. Fig 5f). If the participants did not recall another scene for thirty seconds, the free recall was finished. Subsequently, detailed questions were asked about the scenes that had previously been recalled (cued recall). Accordingly, no detailed questions were asked about those scenes that were not recalled during free recall. For example, one video showed a kart race. If the subjects recalled this scene during free recall, they were asked during cued recall what colors the boundary of the karting track had (cf. Fig 5b & Table 3).

Statistical Analysis

For analysis of the sense of presence, the IPQ subscales *General Presence, Spatial Presence, Involvement,* and *Realness* were calculated. *Cronbach's* α was calculated per scale except for the one-item-scale *General Presence.* Group differences were analyzed using the one-tailed Mann-Whitney-*U*-test as normal distribution was not given for the subscale *General Presence* ($p < 0.05$), and the effect size r was calculated. The effect size estimate r is a correlation coefficient as an alternative to Cohen's d for non-parametric tests (small effect: $r \geq .10$; medium effect: $r \geq .30$; large effect: $r \geq .50$).

The memory performance regarding free recall was calculated as the quotient of the remembered scenes and the total number of presented scenes (free recall performance = recalled scenes/30). Memory performance regarding cued recall was calculated as the number of correctly answered detailed questions and the total number of questions asked, equivalent to the number of recalled scenes (cued recall performance = correct answers/recalled scenes). The group differences were analyzed using the one-tailed unpaired *t*-test due to the directed hypothesis of replicating the memory superiority effect for VR stimuli. Cohen's d was calculated as an estimate of effect size.

Additionally, the recall rate in percent was calculated for each individual video regarding the whole group, the VR group, and the PC group. The *Chi-square* test was used to determine whether individual videos were remembered more frequently by one group or the other.

Results Study 2

Presence

As expected, the VR condition elicited a stronger sensation of feeling present in the virtual environment as compared to the PC condition, reflected in all IPQ scales (general presence: $U = 240.50$, $z = -3.17$, $p = .001$, $r = 0.41$; spatial presence: $U = 205.00$, $z = -3.63$, $p < .001$, $r = 0.47$; involvement: $U = 213.00$, $z = -3.51$, $p < .001$, $r = 0.45$; realness: $U = 335.00$, $z = -1.71$, $p = .044$, $r = 0.22$). Cronbach's α indicates acceptable to good reliability for all scales (all $\alpha > 0.73$; *see* Table 4).

Memory Performance

Participants of the VR condition freely recalled 55.6% of the scenes and hence, ca. 6% more as compared to the PC condition, who remembered approximately 49% ($t(58) = 1.98$, $p = .026$, $d = 0.50$, $M_{\mathrm{VR}} = 0.556$, $M_{\mathrm{PC}} = 0.491$; see Fig. 6). However, the performance of the groups did not

Table 3 Content of the 30 exemplary videos from the luVRe that were used as stimuli

Video	Content	Detail question for cued recall
Cowshed	Calves in a barn with straw and dim light.	Was a lamp switched on in the cowshed?
Discotheque	Party in a discotheque with blue and red headlights, a DJ and dancing people	Did the blue light in the club come from the left or the right?
Wood in winter	Light forest with leaves and snow on the ground. In the background is an old stone bridge	Were there leaves on the ground in the forest?
Fire engine	Interior of a fire engine. Four firefighters enter the vehicle.	Did the firemen wear helmets?
Soccer training	A soccer team is training outside	Did the soccer player kick the balls to the left or right side?
Break dancing	A group of dancers performs break-dance at a festive event	What color was the "HULL" sign?
Kart race	View on a go-cart track while a race is ongoing. One driver crashes into the boundary in front of the viewer.	What were the colors of the go-kart track?
Mixed Marshall arts	Two men are training and fighting (Mixed Marshall Arts)	Were both fighters wearing long pants?
Motocross stunts	Two motocross drivers offer a show and jump over cars and pallets	What color was the motocross rider's clothing?
Trauma room	Interior view of a trauma room. A patient in a wheelchair is visible through one door.	Were all doors in the trauma room opened?
Pole dancing	A young girl in a tight suit pole dances	Were there mirrors in the pole dancer's room?
Bathroom	A plain bathroom. The window is open but blocked by a lattice.	Could you have climbed through the bathroom window?
Horse riding	A woman rides on a horse	Was the equestrian wearing a scarf?
Water slide	Young people sliding down a pool slide	What color was the tire that the man was wearing at the swimming pool?
Bar	A barkeeper serves beer. A woman sits next to the viewer at the bar.	What drink was served in the bar?
Dentist's chair'	First-person view from a dentist's chair in a treatment room	What color was the dentist chair?
Arctic foxes	An animal keeper feeds arctic foxes in the zoo enclosure	What color was the fox keeper's clothing?
Motorway bridge	View on the motorway from a bridge	What color was the railing of the motorway bridge?
Car showroom	Interior view of a car showroom	Which car brand was sold in the car showroom?
Puppies	A room full of puppies, furnished with straw, mattresses, and toys	Were the puppies outdoors or indoors?
Mining tunnel	An empty, sparsely lit mining tunnel	Was there a person in the mining tunnel?
Funeral	Event room, in which a closed coffin is set up, surrounded by flowers and candles	Were there candles around the coffin?
Supermarket	A young woman doing grocery shopping	Was the woman in the supermarket wearing her hair loose?
Pianist	A young pianist plays a classical composition	Was there more than one piano in the room?
Fitness class	A fitness trainer leads a fitness class with tap boards and weights.	Did the fitness class participants have tap boards?
Karate fight	A training fight is performed in a dojo	Who won the karate match?
Orchestra concert	An orchestra gives a concert in a slightly illuminated church	Who was the central figure in the church?
Surgery room	Surgeons perform a neurological operation	Were the doctors in the surgery room wearing white lab coats?
London Eye	View on London eye from a bridge	What color was the ferris wheel?
Time Square	View on the busy time square, a tourist poses for photographs	What gesture does the tourist make on Times Square?

differ regarding cued recall ($t(58) = -1.35$, $p = .09$, $d = 0.35$, $M_{\mathrm{VR}} = 0.595$, $M_{\mathrm{PC}} = 0.64$). Interestingly, the participants of the VR condition answered proportionally fewer questions correctly (59.5%) than participants of the PC condition (64.4%; see Fig. 6).

The recall rate per individual video ranged from 16.7% - 91.7% for the total group (VR: 16.7% - 90%; PC: 16.7% - 93.3%; see Table 5). Notably, the most frequently remembered videos were: Puppies, mixed martial arts, karate fight, trauma room, surgery room, horse riding, and cowshed (all recall rates >70% for the whole group, see Table 5). Four videos were significantly more frequently recalled by the VR group as compared to the PC group (surgery room, horse riding, cowshed, break dancing, see Table 5). However, no further significant differences between both groups were found on the level of the

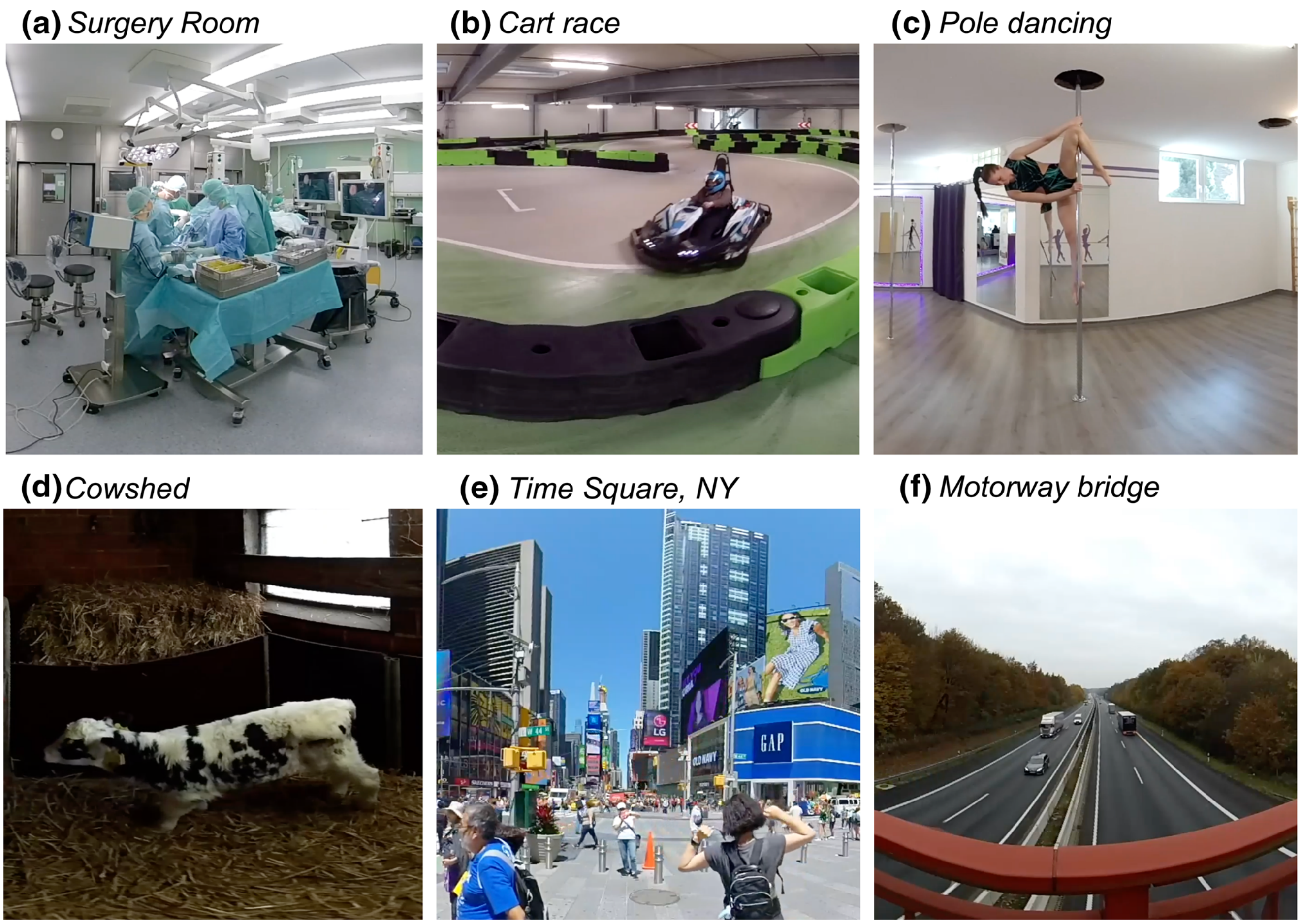

Fig. 5 Exemplary stimuli. *Note.* The screenshots were taken from six of the 30 videos used as stimulus material, depicting a *surgery room* (**a**), a go-cart race (**b**), pole dancing (**c**), a cowshed (**d**), the Time Square, NY (**e**), and a motorway bridge (**f**). The slightly distorted display of the screenshots results from being captured with a conventional video player instead of a 360° compatible program. During the experiment, the videos were displayed without distortion

individual videos. Descriptively, the recall rate was higher in the VR group for 17 of the videos and equal in both groups for seven videos.

Discussion Study 2

The aim of study No. 2 was to replicate the memory superiority effect of VR experiences and shed new light on previously inconsistent results (Kisker et al., 2019b; Krokos et al., 2019; Schöne et al., 2019; Smith, 2019). As expected, the participants in the VR condition reported a higher sense of presence, which presumably is the most important factor underlying the also obtained VR memory superiority effect for the free recall (see Sauzéon et al., 2012). Both effects are important markings towards a broader application of VR tools in experimental psychology. The rapid mode of serial video presentation aligned with conventional paradigms yielded the same effects as previous VR studies investigating mnemonic mechanisms in a single environment. This is remarkable as the mode of presentation in this study might have a diminishing effect on the factors constituting the unique VR experience: The timed changes of place participants underwent is inconsistent with the laws of physics and make the user repeatedly aware that they are just in a VR simulation.

The cued recall did not yield significant results, meaning that no group exhibited a higher recall rate for scenic details. However, an effect could have been expected. Specifically, the feeling of being present in the scene might facilitate the

Table 4 Descriptive statistics and reliability of the IPQ presence scales for both groups

	M_{VR}	SD_{VR}	M_{PC}	SD_{PC}	Cronbach's α
General Presence	0.90	1.47	−0.53	1.70	–
Spatial Presence	3.40	4.77	−2.77	6.47	.747
Involvement	2.80	5.47	−2.53	5.28	.830
Realness	−0.73	3.46	−2.33	4.33	.737

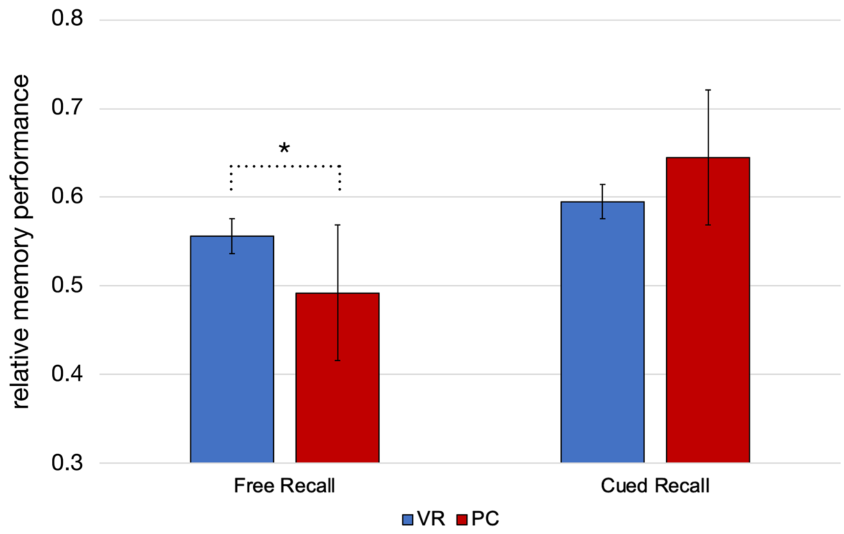

Fig. 6 Relative memory performance in free and cued recall separately for both groups. *Note.* The error bars depict the standard error of the mean. Significant differences are marked (* $p < 0.05$)

Table 5 Recall rate in percent and Chi-square test per video

	Recall rate in percent			Chi-square test		
Video	Total group	VR group	PC group	*Chi-square*	*df*	*p*
Motorway bridge	45.00	56.70	33.30	3.30	1.00	0.069
Car showroom	16.70	16.70	16.70	0.00	1.00	1.000
Bathroom	50.00	56.70	43.30	1.07	1.00	0.302
Bar	41.70	43.30	40.00	0.07	1.00	0.793
Funeral	50.00	53.30	46.70	0.27	1.00	0.606
Mixed martial arts	73.30	73.30	73.30	0.00	1.00	1.000
Discotheque	43.30	43.30	43.30	0.00	1.00	1.000
Fire engine	30.00	30.00	30.00	0.00	1.00	1.000
Fitness class	41.70	36.70	46.70	0.62	1.00	0.432
Arctic foxes	60.00	60.00	60.00	0.00	1.00	1.000
Soccer training	35.00	30.00	40.00	0.66	1.00	0.417
Puppies	91.70	90.00	93.90	0.22	1.00	0.640
Karate fight	76.70	76.70	76.70	0.00	1.00	1.000
Kart race	48.30	53.30	43.30	0.60	1.00	0.438
Orchestra concert	35.00	36.70	33.30	0.07	1.00	0.787
Pianist	38.30	40.00	36.70	0.07	1.00	0.791
Trauma room	75.00	83.30	66.70	2.22	1.00	0.136
Motocross stunts	51.70	50.00	53.30	0.07	1.00	0.796
Surgery room	73.30	86.70	60.00	5.46	1.00	0.020
Horse riding	73.30	86.70	60.00	5.46	1.00	0.020
Pole dancing	53.30	56.70	50.00	0.27	1.00	0.605
London Eye	38.30	46.70	30.00	1.76	1.00	0.184
Water slide	26.70	20.00	33.30	1.36	1.00	0.243
Cowshed	78.30	90.00	66.70	4.81	1.00	0.028
Supermarket	38.30	43.30	33.30	0.64	1.00	0.426
Break dancing	61.70	76.70	46.70	5.71	1.00	0.017
Time Square	51.70	56.70	46.70	0.60	1.00	0.438
Mining tunnel	55.00	50.00	60.00	0.61	1.00	0.436
Wood in winter	56.70	56.70	56.70	0.00	1.00	1.000
Dentists' chair	61.70	66.70	56.70	0.64	1.00	0.426

memory for objects of interest within reach. However, our experiment did not completely leverage the affordance of VR as the questions for the cued recall were rather unspecific and did not follow a clear structure, which might account for the lack of an effect. Alternatively, the free recall task could have led to a likewise diminished cued recall effect based on the retrieval-induced forgetting effect (Ciranni & Shimamura, 1999): Successful recall of a scene could impair the recall for details in the second recall. As the cued recall followed the free recall in both conditions, participants in both groups were likewise affected. Future studies might omit the first stage in order to investigate scene detail knowledge. A field of research which could benefit from luVRe is research on autobiographical memory. Especially immersive media seem to aid free recall (Ernstsen et al., 2019; Harman et al., 2017; Ventura et al., 2019) as it is the mode of retrieval of autobiographical memory and commonly used for research on unique, lifelike events (Oedekoven et al., 2017).

Conclusion

Virtual reality could be a valuable extension for the toolbox of experimental psychology. Two experiments have provided evidence that cognitive-affective psychological science might benefit from the use of VR paradigms. Study No. 1 showed that presence and especially three-dimensionality fundamentally alter motivational processing and the perceived valence of stimulus. The driving factors underlying these effects have yet to be determined. However, study No. 1 provides first evidences that when presenting the same material under realistic as opposed to two-dimensional conditions the brain exhibits different functional properties. Study No. 2 replicated the memory superiority of virtual reality over on-screen presentation under the aggravated conditions of a fast-paced, everchanging stimulus set. This rather conventional mode of presentation has proven to be capable to facilitate the formation of autobiographical memories (e. g. Schöne et al., 2019; Kisker et al., 2020). Virtual experiences with material from the luVRe database thus are processed with the same mnemonic mechanisms as real-life experiences making the case for their realness and their feasibility for VR based research and aiming at reproducing real-life scenarios. A field of research, which could benefit from luVRe is research on autobiographical memory. Especially immersive media seem to aid free recall (Ernstsen et al., 2019; Harman et al., 2017; Ventura et al., 2019) as it is the mode of retrieval of autobiographical memory and commonly used for research on unique, lifelike events (Oedekoven et al., 2017).

Concludingly, VR combines the best of two worlds: Firstly, the enhanced realism of immersive simulations facilitates more naturalistic processing. As the brain has evolved under three-dimensional conditions throughout its evolutionary developmental history, testing the brain's normal mode of operation significantly enhances the ecological validity of psychological science. Secondly, by using luVRe's stimuli, high experiment control as the key feature of laboratory conditions is preserved. Most importantly, luVRe is easy to use as it does not require extensive technical skills which normally are the bottleneck for VR experiments. The videos can be arranged e. g. in a sequential order using video editing software and displayed with respective video players on any kind of VR headset. Moreover, they are particularly high in realism due to their photo-realistic appearance. Conversely, a programmed environment is a visual replica of a real-life scene and thus can be easily recognized as a simulation. In contrast to luVRe, simulations come with the disadvantage that the facial expressions and gestures of people are difficult to reproduce accurately. Hence, whereas real-life experiments suffer from limited abilities to reproduce social interactions, VR experiments maintain a high degree of realism while being easily replicable.

Application of VR and PC Experiments

It should be noted that the advantages and benefits of VR experiments, as well as the presented results, partially contradicting the prevailing doctrine, do neither render previous results and interpretations invalid nor will strictly controlled laboratory ever be obsolete. Previous methodologies are irreplaceable as they allow researchers to isolate emotional and cognitive mechanisms. The conventional laboratory is thus vital when it comes to the development of models concerning psychological processes. However, we suppose that models and mechanisms should be put up to test under more realistic conditions to explore whether or to what extent they change their mode of operation. Putting them in concert with other processes might show what role they actually play in everyday functioning.

Download, Legal Considerations, and Safety Warnings

The first version of the luVRe database is exclusively accessible for researchers at degree-granting institutions for non-profit (psychological) research. All persons depicted in the database gave their informed consent for a publication solely for scientific purposes. For further information and download, please visit https://www.psycho.uni-osnabrueck.de/fachgebiete/allgemeine_psychologie_i/luvre.html. The database is consistently growing, suggestions are welcome and can be sent, like any other inquiries regarding luVRe or technical questions, to luvre@uni-osnabrueck.de. Initial subjective ratings of valence, arousal, and motivation from pilot tests are provided for some videos and provided alongside the video material catalog.

Most of the scenes in the database are real footage and are not staged. Our first experiences indicate that videos presented under immersive VR conditions elicit much stronger emotional reactions compared to the same videos presented under conventional screen conditions. Consequently, we strongly advise to proceed with caution when setting up VR experiments and thoroughly screen participants, for i.a. (subclinical) emotional trauma or any vulnerabilities and when feasible. Researchers should be aware that their participants could be confronted with injured persons and dead bodies, be screamed at by armed police officers pointing a gun at their head (for a comprehensive account on ethical considerations regarding VR, see Parsons (2019)).

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Declarations

Statement of Ethical Approval All procedures performed in this study involving human participants were in accordance with the ethical standards of the local ethic committee of Osnabrück University and with the 1964 Helsinki Declaration.

Consent to Participate and to Publish All individual participants gave informed written consent to participate in the study and to the anonymized publication of the datasets.

Conflict of Interest All authors declare that they have no conflict of interest.

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2.2 Study 2: *Authentic fear responses in virtual reality: A mobile EEG study on affective, behavioral and electrophysiological correlates of fear*

Abstract

Fear is an evolutionary adaption to a hazardous environment linked to numerous complex behavioral responses, e.g., the fight or flight response, suiting the respective environment. However, for the sake of experimental control, fear is mainly investigated under rather artificial laboratory conditions. The latter transform these evolutionary adaptions into artificial responses, like keystrokes. The immersive, multidimensional character of virtual reality enables realistic behavioral responses, overcoming aforementioned limitations. To investigate authentic fear responses from a holistic perspective, participants explored either a negative or a neutral VR cave. To promote real life behavior, we built a physical replica of the cave, providing haptic sensations. Electrophysiological correlates of fear related approach and avoidance tendencies, i.e., frontal alpha asymmetries were evaluated. To our knowledge, this is the first study to simultaneously capture complex behavior and associated electrophysiologic al correlates under highly immersive conditions. Participants in the negative condition exhibited a broad spectrum of realistic fear behavior and reported intense negative affect as opposed to participants in the neutral condition. Despite these affective and behavioral differences, the groups could not be distinguished based on the FAAs for the greater part of the cave exploration. Taking the specific behavioral responses into account, the obtained FAAs could not be reconciled with well-known FAA models. Consequently, putting laboratory based models to the test under realistic conditions shows that they may not unrestrictedly predict realistic behavior. As the VR environment facilitated non mediated and realistic emotional and behavioral responses, our results demonstrate VR's high potential to increase the ecological validity of scientific findings.

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Authentic Fear Responses in Virtual Reality: A Mobile EEG Study on Affective, Behavioral and Electrophysiological Correlates of Fear

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Fear is an evolutionary adaption to a hazardous environment, linked to numerous complex behavioral responses, e.g., the fight-or-flight response, suiting their respective environment. However, for the sake of experimental control, fear is mainly investigated under rather artificial laboratory conditions. The latter transform these evolutionary adaptions into artificial responses, like keystrokes. The immersive, multidimensional character of virtual reality (VR) enables realistic behavioral responses, overcoming aforementioned limitations. To investigate authentic fear responses from a holistic perspective, participants explored either a negative or a neutral VR cave. To promote real-life behavior, we built a physical replica of the cave, providing haptic sensations. Electrophysiological correlates of fear-related approach and avoidance tendencies, i.e., frontal alpha asymmetries (FAA) were evaluated. To our knowledge, this is the first study to simultaneously capture complex behavior and associated electrophysiological correlates under highly immersive conditions. Participants in the negative condition exhibited a broad spectrum of realistic fear behavior and reported intense negative affect as opposed to participants in the neutral condition. Despite these affective and behavioral differences, the groups could not be distinguished based on the FAAs for the greater part of the cave exploration. Taking the specific behavioral responses into account, the obtained FAAs could not be reconciled with well-known FAA models. Consequently, putting laboratory-based models to the test under realistic conditions shows that they may not unrestrictedly predict realistic behavior. As the VR environment facilitated non-mediated and realistic emotional and behavioral responses, our results demonstrate VR's high potential to increase the ecological validity of scientific findings (video abstract: https://www.youtube.com/watch?v=qROsPOp87I4&feature=youtu.be).

Keywords: authentic fear, virtual reality, mixed reality, mobile EEG, frontal alpha asymmetry, fear behavior

INTRODUCTION

The most salient stimuli that instantly draw attention are biologically relevant stimuli ensuring survival: nutrition, reproduction, and physical dangers (Carretié et al., 2012; Carboni et al., 2017). Among these, threats to physical integrity most inevitably jeopardize survival and immediately trigger complex responses, like the fight-or-flight response (Cannon, 1929). Hence, fear has been extensively investigated ever since (e.g., Fanselow, 1994; LeDoux 1998, 2014; Debiec and LeDoux, 2004; Blanchard and Blanchard, 1969). Several laboratory setups have been used over time to induce fear-related responses under laboratory conditions. One of the most prominent and efficient procedures for fear induction is classical conditioning (e.g., LeDoux, 1998; Jarius and Wildemann, 2015). This method has proven to be successful innumerable times in generating fear of a stimulus that was previously not frightful, assessed by typical fear responses to the conditioned stimulus, such as the startle reflex (e.g., Brown et al., 1951; Grillon and Ameli, 2001). However, conditioning paradigms require laboratory fear acquisition in order to examine fear responses (e.g., LeDoux, 1998), and mostly take only single components of the reaction detached from the overall reaction into account, e.g., the startle reflex, to guarantee high internal validity. More naturalistic assessments are based upon pre-existing fear, for example in behavioral avoidance tasks (BAT). BATs are conventionally used in exposure therapies to estimate the severity of phobias and the treatment's efficacy (see e.g., Bernstein and Nietzel, 1973; Rinck and Becker, 2007). In clinical assessments, BATs are regularly carried out *in vivo*, and therefore allow for holistic responses to the frightful stimulus (e.g., Bernstein and Nietzel, 1973; Koch et al., 2002; Deacon and Olatunji, 2007). However, clinical assessments are indicative of deficient or altered emotional regulation, rather than natural fear reactions (e.g., Hermann et al., 2009; Cisler et al., 2010; Lanius et al., 2010). In contrast, non-clinical applications of BATs broadly rely on finite response options and stimuli, such as pressing a key or pulling a joystick to indicate the urge to avoid or approach an aversive stimulus (e.g., Heuer et al., 2007; Hofmann et al., 2009; Krieglmeyer and Deutsch, 2010). These rather artificial setups neglect that fear is a multidimensional response to a holistic environment and associated with complex behavioral programs, such as the fight-or-flight response to immediate threat (e.g., Cannon, 1929; Lynch and Martins, 2015; Teatero and Penney, 2015).

The complexity and multidimensionality characteristic of real-world experiences can be simulated by sophisticated virtual reality (VR) setups (Slater and Sanchez-Vives, 2016; Parsons, 2019; Pan and Hamilton, 2018; Schöne et al., 2020). In particular, VR offers high levels of sensory cues and fidelity of the virtual environment (VE); (Dan and Reiner, 2017; Riva et al., 2019), resembling a multisensory 3D-environment (Cabeza and Jacques, 2007; Pan and Hamilton, 2018; Parsons, 2019; Schöne et al., 2020). Consequently, users feel actually present and involved into the VE: Being able to manipulate their surroundings, but also to be the subject to the virtual events and actions significantly increases the VE's personal and emotional relevance (Slater and Wilbur, 1997; Kisker et al., 2020; Schöne et al., 2019; Schöne et al., 2020). Over the last couple of years, it has repeatedly been demonstrated that well-designed VEs are capable of eliciting strong emotional responses (e.g., Diemer et al., 2015; Felnhofer et al., 2015; for review see; Bernardo et al., 2020), that even keep up with their real-life counterparts (Higuera-Trujillo et al., 2017; Chirico and Gaggioli, 2019). For example, the exposure to great virtual heights evokes fear responses consistently across various setups as assessed by self-reports, psychophysiological and behavioral responses (Kisker et al., 2019a; Biedermann et al., 2017; Gromer et al., 2018, 2019; Wolf et al., 2020; Asjat et al., 2018). Accordingly, VR has gained great interest as an instrument for fear paradigms. For instance, being submersed into a virtual park at night and seeing distant shadowy silhouettes effectively elicited unease and anxiety in participants (Felnhofer et al., 2015). Thus, VR setups are markedly superior to the use of conventional stimuli, e.g., static pictures, regarding emotion induction and emotional involvement (Gorini et al., 2010).

But even more, a strong sensation of presence and a high degree of immersion increase the chances that participants behave as they would in real-life situations (Blascovich et al., 2002; Slater, 2009; Kisker et al., 2019a). For example, participants effectively adapt their behavior to the environmental conditions by making smaller, slower steps when crossing a beam at a considerable height (e.g., Biedermann et al., 2017; Kisker et al., 2019a). In a similar vein, VR exposure therapies effectively trigger fear responses and modify phobia-related reactions permanently, e.g., concerning acrophobia (e.g., Coelho et al., 2009), arachnophobia (e.g., Bouchard et al., 2006), agoraphobia, and social phobia (e.g., Wechsler et al., 2019). Hence, VR bears the potential not only to elicit real-life processes within a simulation but beyond that, to transfer virtual experiences to everyday life.

Consequently, when exposed to highly emotional and interactive VR scenarios, participants' responses go far beyond self-reports or pressing keys. The use of VR setups enables participants to respond within a much wider behavioral spectrum and most importantly, to react naturally and instantly to stimuli within a fully controllable setup (e.g., Slater, 2009; Bohil et al., 2011; Kisker et al., 2019a). Initial studies elicited fear using highly interactive setups and distinct fear cues. For example, VR horror games such as "The Brookhaven Experiment" Phosphor Games (2016) trigger anxiety by contextual features, such as darkness (e.g., Felnhofer et al., 2015), but beyond that, elicit fear responses to specific stimuli, e.g., zombies approaching the protagonist (e.g., Lin, 2017). Being virtually present and involved in dangerous situations positively correlates with increases in psychophysiological measures of stress, like heart rate (e.g., Higuera-Trujillo et al., 2017; Parsons et al., 2013; Gorini et al., 2010; Kisker et al., 2019a), verbal expressions of fear like screaming, and behavioral coping reactions like dodging or closing the eyes (Lin, 2017). A correspondingly high degree of interactivity allows for the impression of actively manipulating the events, as well as being directly affected by them, and thus facilitates authentic, multidimensional fear responses (Slater, 2009; Lynch and Martins, 2015; Lin, 2017). Whereas conventional laboratory setups have to rely on rather limited or substitutional response options, highly interactive VEs allow for physical movements and full-body responses. Consequently, participants might even fight or flee from fear cues, thus physically approaching or avoiding dangers in order to cope with them.

Markers of those behaviors are electrophysiological correlates of approach and avoidance. While event-related potentials associated with approach and avoidance, like modulations of the late positive potential (e.g., Bamford et al., 2015), reflect fine-grained but only specific parts of the electrophysiological response, oscillatory neuronal dynamics allow for an ongoing assessment of cognitive processes (Bastiaansen et al., 2011). In particular, frontal alpha asymmetries (FAA) have been regarded as a canonical oscillatory correlate of emotional and motivational directions (e.g., Davidson et al., 1990; Coan et al., 2006; Rodrigues et al., 2018; Lacey et al., 2020). According to the valence model of FAA, relatively greater left frontal cortical activity relates to positive emotions and approach, whereas relatively greater right frontal cortical activity relates to negative emotion and withdrawal (Davidson et al., 1990; Davidson, 1998). Later models suggest the corresponding FAAs be indicative rather of the motivational direction, i.e., approach motivation and withdrawal motivation, independent of emotional valence (e.g., Gable and Harmon-Jones, 2008; Harmon-Jones et al., 2010; Harmon-Jones and Gable, 2018). For example, anger, obviously of negative valence, is related to relatively greater left frontal activity (e.g., Gable and Harmon-Jones, 2008). Notably, so far none of these models has emerged as being universally valid. An increasing number of studies offer divergent results and interpretations, adding to the debate about FAAs as indicators of either emotional or motivational directions (for review see e.g., Harmon-Jones and Gable, 2018). Recent models even suggest that FAAs indicate effortful control of emotions rather than emotional directions (Lacey et al., 2020; see also Schöne et al., 2015).

However, the vast majority of studies relating approach and avoidance to FAAs are based upon highly controlled laboratory setups, resembling real-life situations only to a very limited degree. Initial approaches to enhance FAA's generalizability to realistic conditions employed somewhat more immersive, so-called desktop-VR setups (Brouwer et al., 2011; Rodrigues et al., 2018). In particular, Rodrigues et al. (2018) associated active behavior with FAAs as indicated by the motivational direction model: Participants moved *via* joystick through a virtual maze depicted on a conventional desktop, encountering either a sheep, a monster, or a neutral person. Greater left frontal activation was associated with approach behavior and greater right frontal activation with withdrawal behavior respectively (Rodrigues et al., 2018). However, desktop-VR cannot offer as many degrees of freedom as highly immersive VR systems (e.g., HMDs, CAVE), inter alia, stereoscopic 360° view, and physical movements within a VE (e.g., Smith, 2019). This further enables mobile and multi-modal brain/body imaging utilizing head-tracking, motion capture or analysis via video, opening up possibilities for less restricted behavioral reactions to be explicitly recorded, analyzed, and integrated into the research design (Makeig et al., 2009).

Our previous study on FAA in virtual environments has demonstrated the general technical feasibility of combined VR EEG-FAA measurements (Schöne et al., 2021; see also Lange and Osinsky, 2020 for mobile EEG). Most importantly, the study provided the first evidence that the same stimulus material presented in VR compared to a 2D condition yields different motivational patterns reflected in the FAA data. Although the immersive nature of VR provides a more realistic environment compared to a conventional laboratory setting, a key element of the everyday experience is not yet part of the equation: Motivational tendencies, as reflected by FAA, are accompanied by a corresponding behavior adapted to the situation in which it occurs. Whereas in laboratory settings, approach or withdrawal motivation is indicated by keystroke (e.g., Gable and Harmon-Jones, 2008), the advantage of VR as a tool is the creation of controlled environments in which the participant can roam and respond freely. Consequently, the question remains whether FAAs would follow the same trend as proposed by Rodrigues et al. (2018) under highly immersive conditions that allow for physical, realistic approach and avoidance behavior.

Going beyond previous VR studies on fear, the aim is not only to capture affective fear responses by means of subjective reports elicited by the VR environment, but to examine holistic fear responses, comprising full-body behavioral expressions of fear, and to put to the test whether corresponding electrophysiological correlates of approach and avoidance behavior obtained under conventional laboratory conditions apply to highly immersive VR setups. To this end, we set up an EEG-VR study in which participants explored either a neutral or a negative, i.e., frightful cave. We aimed to situate participants in an immersive environment triggering a strong, authentic fear response. As a neutral control, a second group of participants explored a non-emotional cave. To enhance the feeling of being present in the VE, and thereby impression of being personally and physically affected by the environment and events, we build an exact, spatially aligned, physical replica of the cave - touching the cave's stone wall in the virtual world thus led to a corresponding physical sensation (see Kisker et al., 2019a; Biedermann et al., 2017). As interactivity is a major factor enhancing fear in VR setups (Lynch and Martins, 2015; Madsen, 2016; Lin et al., 2018), participants physically walked through the cave holding a controller appearing as a flashlight in VR. Thus, their virtual movements corresponded to their physical movements. Above all, they gained the impression of being able to touch their surroundings and, more importantly, of being touched by them in return.

Affective Response

Due to VR's immersive character and based on previous findings (e.g., Lin, 2017; Felnhofer et al., 2015), we expected participants of the *negative* condition to report greater negative affect, acute fear, and presence compared to the *neutral* group (e.g., Felnhofer et al., 2015; Kisker et al., 2019a; Diemer et al., 2015).

Behavioral Response

Going beyond the frequently investigated affective response, we hypothesized that participants would adapt their behavior to their environmental conditions. Specifically, the *negative* condition is supposed to elicit complex fear behavior, i.e., in terms of the fight-or-flight response. The cave was designed in such a way that when participants encountered the werewolf, we expected them to exhibit either one of two behaviors: Firstly, advance toward the werewolf risking physical encounter to get past it. Secondly, to retreat to safe distance and wait to see how the situation develops to plot a safe escape route. As fearful, cautious behavior is associated with slower walking compared to harmless situations (Biedermann et al., 2017; Kisker et al., 2019a), the *negative* condition might exhibit longer exploration times compared to the *neutral* condition.

Psychophysiological Response

In line with the expected affective and behavioral responses, we assumed corresponding psychophysiological responses, i.e., decreases in heart rate variability (HRV; see e.g., Castaldo et al., 2015) to indicate increased stress levels in the *negative* condition. In contrast, we assumed that the *neutral* group would not exhibit any fear-related behavioral responses and stay unaffected in respective psychophysiological responses.

Electrophysiological Response

Derived from the aforementioned theoretical models on frontal alpha asymmetry, we hypothesized that the FAAs would significantly differ between conditions as a function of the exhibited behavioral responses. In particular, we expected avoidance behavior to be linked to relatively greater right cortical activity, and approach behavior to relatively greater left cortical activity.

METHODS

Participants

The study was approved by the local ethics committee of Osnabrück University. Ninety-six participants were recruited from the local student population, gave their informed written consent, but were blind to the research question and experimental conditions. They were screened for psychological and neurological disorders using a standard screening for mental disorders and distress (anamnesis). All had a normal or corrected-to-normal vision. When vision correction was necessary, only participants wearing contact lenses could participate, not those wearing glasses. The participants were randomly assigned to one of two conditions (*negative* vs. *neutral*; see below) and blind to which condition they would participate in. As stated in the hypothesis, the cave was designed in such a way that we expected two behavioral patterns to emerge within the *negative* condition. Based on this assumption, twice as many participants were assigned to the *negative* condition as to the *neutral* condition.

The sample size was determined based on previous studies that conducted EEG measurements in a VR condition (Kisker et al., 2020; Lange and Osinsky, 2020; Schöne et al., 2021). Based on these studies, we aimed for a sample of about 25 participants per subgroup (see *Exploration time and behavior*). Although data acquisition was stopped due to the COVID-19 pandemic, we are optimistic that we obtained an adequate number of data sets corresponding to groups sizes implemented in previous VR studies (see Schöne et al., 2019; Kisker et al., 2020; Lange and Osinsky, 2020; Schöne et al., 2021). The participants received either partial course credits or 15€ for participation.

One participant was excluded during anamnesis and five participants of the *negative* condition terminated the experiment during the virtual simulation. Nine participants were excluded from analysis due to insufficient EEG data quality (n = 1) or technical problems during the virtual experience (n = 8). Hence, a final sample size of N = 81 participants was obtained for analysis (negative: n = 54, M_{age} = 21.67, SD_{age} = 3.57; 81.5% female, none diverse, 13% left-handed; neutral: n = 27, M_{age} = 23.15, SD_{age} = 2.98; 59.3% female, none diverse, none left-handed). The high proportion of female participants results from a random sample with the majority of local psychology students being female. Although women are more likely to suffer from anxiety disorders and experience fear more frequently in their lives than men (e.g., McLean and Anderson, 2009), we found no significant differences between groups concerning general anxiety and current state of mind before the cave exploration. Hence, we assume that the gender imbalance did not affect the results obtained from group comparisons (see results).

Experimental Conditions and Setup

The experiment was comprised of two experimental conditions (*negative* vs. *neutral*). For both conditions, a mixed-reality design was implemented. A VR cave was designed in Unity 5 (version 2018.3.0f2, Unity Technologies, San Francisco, United States) and a physical replica of the cave was set up in the laboratory. The physical setup resembled the virtual layout and walls, allowing for haptic sensations when touching the virtual surroundings. Relevant objects within the cave were physically represented: Ivy vines at the cave's exit were mimicked by jute ropes, a corpse was mimicked by a life-size puppet, tree trunks and rocks by paper-mâché replicas (**Figure 1**). The cave's layout and the path running through it were identical for both conditions. There was only one possible path through the cave. The virtual environment was presented with a wireless version of the HTC Vive Pro (HTC, Taoyuan, Taiwan) head-mounted display (HMD). Movement within the cave was implemented through active, physical walking. All participants held a Vive controller in their dominant hand, serving as a flashlight.

The difference between the caves was achieved by atmospheric elements alone as outlined in detail below. Events related to the atmospheric elements, e.g., the onset of wind howling, were automatically triggered depending on the position of the participant within virtual the cave. Each event was triggered only once per participant. Exemplary videos of the scenery and a video abstract are provided (see availability of data, material, and code).

Exploration of the Negative Cave

The *negative* condition was designed as a gloomy environment. The cave was only dimly illuminated. A mutilated corpse, the sound of crying, and a werewolf were used as fear-triggering stimuli (**Figure 1B1,D1**). In the cave's entrance area, it was obvious that a frightening environment was to be expected, with weapons and corpses laying on the floor at distance (**Figure 1C1**). The area

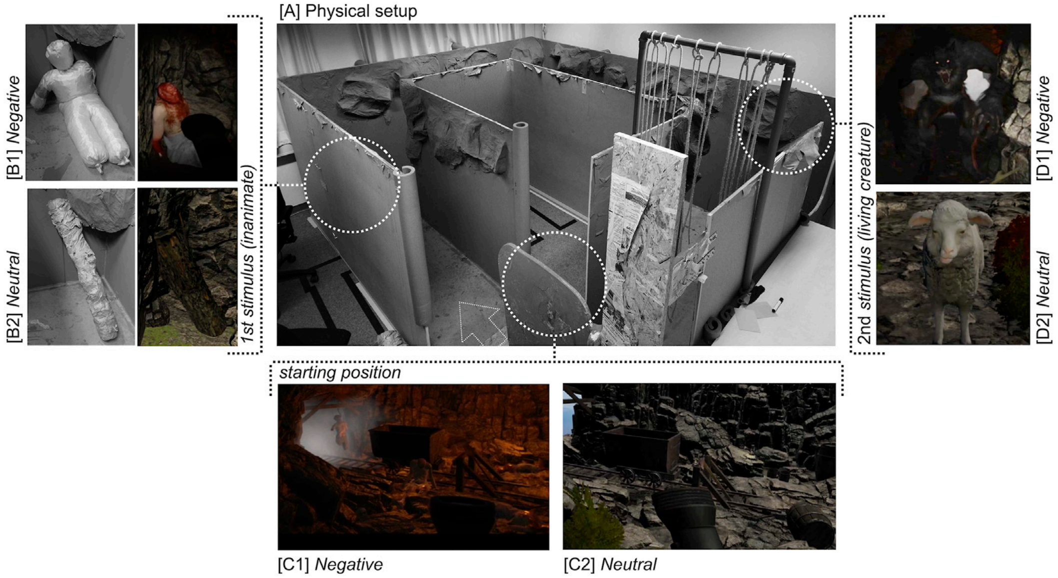

FIGURE 1 | Illustration of the (physical) cave and respective stimuli per condition. Panel **(A)** depicts the physical replica of the cave which participants walked through. The dotted white arrow indicates the initial direction in which the participants moved through the cave. The position of relevant creatures/objects in their virtual and physical form (see panels **(B)** and **(D)**) are indicated respectively.The cave's entrance area (panel **C**) served as an indicator of what environment was to be expected. It gave participants an immediate chance to terminate the experiment.

aimed to allow the participants to immediately terminate the experiment if they did not dare to explore the negative, i.e., frightful cave. To navigate through the cave, participants had to turn around 180°. At a distance of about 2 m lay a mutilated corpse at the first turn-off of the path (**Figure 1B1**). Shortly before reaching the corpse, crying could be heard. The participants had to step around the corpse to follow the path any further. Shortly before they reached the next turn-off, a monstrous roar and footsteps could be heard. Once they had passed this turn-off, a 2 m high werewolf was visible, walking towards the participants from the other end of the cave up to a fixed point at the third turn-off of the cave (**Figure 1D1**). Participants did not know that the werewolf would not approach them any further than to this fixed point. The werewolf stopped at the junction, leaving room to pass it, still roaring and striking towards the participants. Participants had to walk towards the werewolf and turn off directly in front of it to reach the cave's exit (**Figure 2**).

Exploration of the Neutral Cave

The *neutral* condition was designed as a non-emotional environment. The cave was also only dimly illuminated, but brighter than the negative cave. All stimuli of the *negative* condition were replaced by neutral stimuli. In detail, the corpse was replaced by a tree trunk, the werewolf by a sheep (**Figure 1B2,D2**), and wind howling replaced the sound of crying (**Figure 2**). The entrance area of the cave was designed plainly. Wooden barrels and buckets lay in the places where the *negative* condition contained weapons and corpses (**Figure 1**, C2). To navigate through the cave, participants had to turn around 180°. At the first turn-off of the path lay a tree trunk (**Figure 1B2**). Shortly before reaching the tree trunk, wind howling could be heard. Shortly before the second turn-off, a bleating sheep and its footsteps could be heard. Stepping around this turn-off, a sheep became visible, walking towards the participant from the other end of the cave up to a fixed point at the third turn-off of the cave (**Figure 1D2**). Participants did not know that the sheep would not approach them any further than to this fixed point. The sheep stopped at the junction, leaving room to pass it, still bleating and eating grass. Participants had to walk towards the sheep and turn off directly in front of it to reach the cave's exit (**Figure 2**).

Procedure

Participants were blind to the experimental conditions and design but were informed that the cave might be perceived as unpleasant. During experiment preliminaries, it was checked whether participants had gained any previous information about the experiment's research objective, content, or design. If any of this was true, they were excluded from the experiment. Participants were screened for psychological and neurological disorders using a standard screening for mental disorders. Special attention was paid to anxiety disorders, subclinical fears, and current emotional strain. If participants were currently experiencing neurological or psychological disorders or were currently undergoing psychological, psychiatric, or neurological treatment, they were excluded from participation in the study.

Participants were asked to fill out a set of questionnaires, including the German versions of the *State-Trait-Anxiety-Inventory, trait scale* (*STAI-T*; Laux et al., 1981), the *Sensation Seeking Scale Form-V* (*SSS-V*; Zuckerman, 1996), the *E-Scale* (Leibetseder et al., 2007), the BIS/BAS scale (Carver and White, 1994; Strobel et al., 2001), *the reinforcement sensitivity theory personality questionnaire* (RST-PQ; Corr and Cooper,

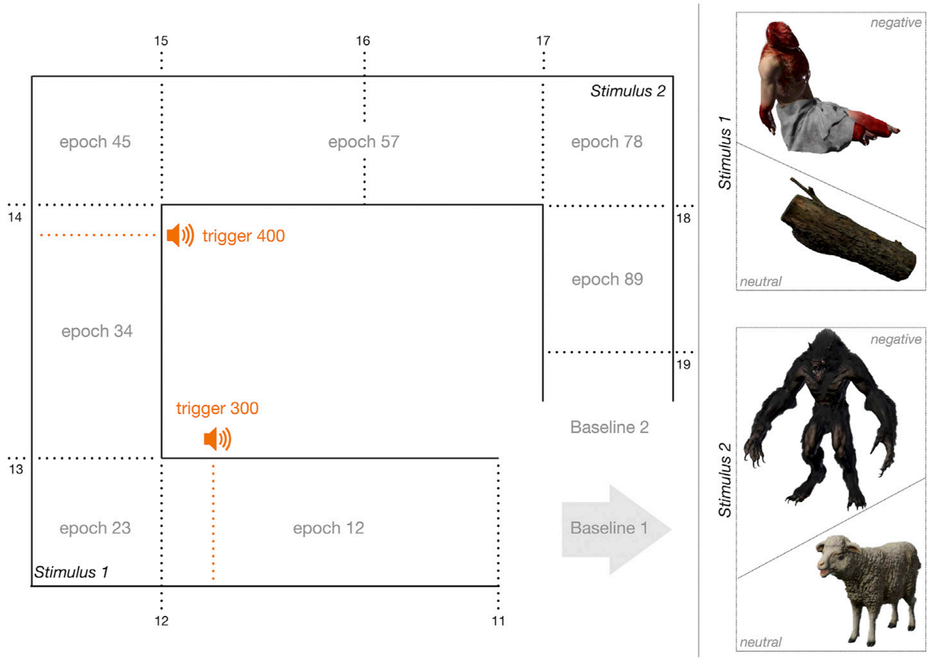

FIGURE 2 | Schematic layout of the virtual cave and exploration epochs. The gray arrow indicates the initial position and the gaze direction for all participants. The positions of relevant objects (see stimuli 1 and 2) are indicated respectively. Dotted lines mark the positions and triggers sent to EEG. The sections of the route through the cave are marked as epochs. For example, epoch 12 denotes the section between triggers 11 and 12. Prominent event within the cave are marked respectively. Epoch 12: Walking towards the corpse/tree trunk and sound of crying/wind howling; epoch 34: Walking away from the corpse/tree trunk and sound of roaring/bleating; epoch 57: Walking towards the werewolf/sheep; Trigger 300: Crying/wind sounds; Trigger 400: Roaring/bleating.

2016) and *revised paranormal belief scale* (RPBS; Tobacyk, 2004). Afterward they were equipped with a wireless mobile EEG system and ECG electrodes (see electrophysiological recordings). For the assessment of their current mood, participants filled out the German version of the *Positive and Negative Affect Schedule* (*PANAS*; Krohne et al., 1996) immediately before instructions.

Participants were instructed that their task would be to explore a cave and find its exit, leading into a village. They got no information concerning the cave's layout or size in advance. They received no prior information about the cave's affective design and stimuli, like sheep, werewolf, or corpse. If they were unable to find the exit or did not want to proceed with exploring the cave, they were free to return to their starting position or terminate the experiment. They were instructed how to use the controller as a flashlight and to move physically through the cave. All participants were instructed to immediately terminate the experiment if they felt too uncomfortable (both physically or mentally).

Participants were equipped with a wireless version of the *Vive Pro* HMD before entering the VR laboratory and did not see the physical setup of the cave at any time before the virtual experience started. To increase the participants' immersion and maintain it during the experiment, any communication with the investigators was stopped completely from the moment they entered the experimental room. Participants were informed that the investigators would not communicate with them or respond to any speech as long as they were in the cave unless they gave a predetermined command to terminate the experiment.

An ECG baseline measurement was recorded in a plain default VR room with the HMD turned on. Afterward the cave simulation was launched. Participants were free to start exploring the cave as soon as they felt comfortable doing so. When they left the cave through the exit, they entered a safe, pleasant-looking fishing village. Once participants reached the village, they stood still for 30 s, allowing for another baseline measurement. Afterward they were distinctly addressed by the investigator and informed that the equipment would be removed from them. They immediately left the VR laboratory. If participants terminated the experiment at an early stage, the environment was immediately switched to the safe fishing village to release the participants from the unpleasant environment as quickly as possible.

To assess mood and the sense of presence, participants were asked to filled out the *PANAS*, the *Igroup Presence Questionnaire* (*IPQ*; Schubert et al., 2001), and an in-house post-questionnaire asking about the emotional and motivational experiences in the cave. The latter included a visual analog scale (VAS) to determine the physical distance to either the werewolf or the sheep which participants preferred (zero up to 10 m). Before participants left the laboratory, they were rewarded with either partial course credits or 15€. The principal psychological investigators ensured that the participants felt safe and sound after the experiment.

Pre-Processing

Electrophysiological Recording and Pre-processing

For EEG-data acquisition, the mobile EEG-system LiveAmp32 by Brain Products (Gilching, Germany) was used. The electrodes were applied in accordance with the international 10–20 system. An online reference (FCz) and ground electrode (AFz) were included. The impedance of all electrodes was kept below 15 kΩ. The data was recorded with a sampling rate of 500 Hz and online band-pass filtered at 0.016–250 Hz. Triggers marking the position of the participant within the cave and the onset of virtual events (e.g., wind howling, monstrous roar, etc.; see **Figure 2**) were transmitted from Unity to Lab Streaming Layer (LSL by SCCN, https://github.com/sccn/labstreaminglayer), which was used to synchronize the EEG data stream and Unity triggers.

All pre-processing steps serve the function of ensuring robust data quality and comparability. In particular, the aim is to reduce the amount of variance caused by common EEG artifacts (e.g., due to eye blinks). The EEG data was analyzed using MATLAB (version R2020b, MathWorks Inc) and EEGLAB (Delorme and Makeig, 2004). The continuous EEG data was bandpass-filtered between 1Hz, reducing slow drifts, and 30 Hz to remove high-frequency artifacts like electrical line noise (see Cohen, 2014). The average reference was used for further offline analysis as recommended for large sets of electrodes (see Cohen, 2014). Artifact correction was performed using "Fully Automated Statistical Thresholding for EEG artifact Reduction" (*FASTER*; Nolan, Whelan and Reilly, 2010). In brief, this procedure automatically detects and removes artifacts, like blinks and white noise, based upon statistical estimates for various aspects of the data, e.g., channel variance. *FASTER* has high sensitivity and specificity for the detection of various artifacts and is described in more detail elsewhere (e.g., Nolan et al., 2010). Due to recommendations for the use of *FASTER* with 32 channel setups, independent component analysis (ICA) and channel interpolation were applied, whereas channel rejection and epoch interpolation were not applied. Each electrode was detrended separately to ensure the same statistical properties for the time series (Cohen, 2014) before segmenting the data into epochs based upon the position triggers. The segmentation of the continuous EEG data into epochs matching the cave sections enabled a more differentiated analysis of the cave exploration. Per epoch, a windowed fast Fourier transform (FFT) was calculated to isolate alpha-band-specific activity (8–13Hz; Berger, 1929). To this end, a hamming window with a length of one second and 50% overlap was applied. The mean FFT score was logarithmized to calculate alpha-band power. For the calculation of the FAA score, the electrode F4 was subtracted from the electrode F3 [logarithmized left alpha power minus logarithmized right alpha power; $\ln(\mu V^2)$]. The former steps to calculate FAAs follow the standard procedure recommended by (Smith et al., 2017).

Exploration time and Behavior

Exploration time was measured in seconds from the initial entrance into the cave (marker 11, **Figure 2**) to exiting the cave (marker 19, **Figure 2**) and for the path section along which participants headed directly towards the werewolf/the sheep (epoch 57).

As expected, the examination of the video recordings of the cave exploration revealed two different behavioral patterns manifested within the *negative* condition, subdividing the *negative* group into two subgroups: When first encountering the werewolf, participants of the *negative* group either retreated, i.e., hesitated or hid behind a former wall (subgroup labeled "*hesitating*"), or quickly advanced toward the werewolf to get past it, hastening around the cave's next turn-off (subgroup labeled "*hastening*"). They were assigned to the subgroups by the assessment of three investigators. To cross-check the division into the three subgroups, we implemented a video rating of the participants' fear behavior by blind raters (see **Box 1**). Since the blind ratings favored the classification of the subgroups (see **Box 1**), the investigators' proposed subdivision was adopted (*hesitating* group: n = 33, M_{age} = 21.70, SD_{age} = 3.85, 87.9% female, 87.9 right-handed; *hastening* group: n = 21, M_{age} = 21.62, SD_{age} = 3.17, 71.4% female, 85.7% right-handed; *neutral* group: n = 27, M_{age} = 23.15, SD_{age} = 2.98, 59.3% female, all right-handed). We provided an analysis of both conditions (*negative* versus *neutral*) without subdivisions into the *hastening* group and the *hesitating* group as supplementary material (see **Supplementary Material S1**).

Cardiovascular Measurements and Pre-processing

A three-channel ECG (Brain Products, Gilching, Germany) was applied and transmitted to the mobile EEG system. Electrodes were placed at the left collarbone, the right collarbone, and at the lowest left costal arch. The ECG was recorded synchronously with the EEG data.

The ECG data was segmented into the baseline measurements before the start of the cave exploration (60 s) and directly after leaving the cave, i.e., standing in the village (30 s). ECG measures during cave exploration were not further analyzed due to insufficient data quality. Participants who were excluded due to technical problems or insufficient EEG data quality and those who terminated the experiment early were excluded from ECG analysis. The datasets were further preprocessed using BrainVision Analyzer 2.2.0 (Brain Products, Gilching, Germany). Datasets were filtered between 5 and 45 Hz to remove low and high-frequency artifacts. Additionally, a notch filter (50 Hz) was applied. An automatic R-peak detection was applied and visually counterchecked. 14 datasets were excluded due to insufficient ECG quality during at least one of both baselines. For the remaining 67 datasets ($n_{\text{hesitating}} = 29$; $n_{\text{hastening}} = 18$; $n_{\text{neutral}} = 20$), the classical HRV parameter, i.e., the root mean square of successive differences (rmSSD) was calculated per baseline using MATLAB. The parameter rmSSD was chosen for analysis as it is recommended for ultra-short-time measurements (10—60 s; Shaffer and Ginsberg, 2017). The individual change in rmSSD between both baselines was calculated per participant and averaged per group for comparisons (delta = baseline 2—baseline 1; see **Figure 2**).

BOX 1 | Cross-check of group subdivision by blind rating

Procedure: A blind video rating was conducted to check the subdivision into the subgroups *hesitating*, *hastening,* and *neutral* based on three investigators' assessment. To this end, recordings of the participants exploring the cave were used. The recordings did neither reveal the participants' identity, nor in which experimental condition they were, nor what they saw in the virtual environment. Only their behavior within the physical replica was visible. Videos of participants who terminated the experiment ($n = 5$) or did not agree to the use and publication of the recordings ($n = 4$) were not included in the rating. The naive raters' task was to evaluate to what extent the person in the video showed fear in their behavior. To do so, they were asked to rate the person's fear on a scale from zero (*no fear at all*) to six (*very strong fear*). Each rater evaluated each of the videos ($n = 77$) in randomized order. They were allowed to take breaks if needed.

Blind raters: Twenty-seven blind raters completed the video rating. It was ensured that none of the raters had prior knowledge of the original study, that none participated in the original study, and that none suffered from any psychological or neurological conditions. Four raters were excluded due to the anamnesis' exclusion criteria, resulting in $n = 23$ valid ratings ($M_{age} = 21.74$, $SD_{age} = 2.54$, 20 female, 3 male, none diverse). To ensure the raters' aptitude, their empathic ability and emotional competence were assessed using the German versions of the e-scale (Leibetseder et al., 2007), and the self-assessment of emotional intelligence (SEK-27; Berking and Znoj, 2008). They were blind to the content, experimental conditions, and objectives of the original study.

Statistical analysis: Per rater, mean fear scores were calculated. For this purpose, the individual video ratings were averaged based on conditions (*negative* vs. *neutral*), as well as based on the previous division of subjects into subgroups (*hesitating* vs. *hastening* vs. *neutral*). These mean fear scores were tested for normal distribution using the Shapiro-Wilk test and further analyzed using separate *t*-tests for dependent samples.

Results: Raters were of average empathic ability ($M = 97.10$) and emotional intelligence ($M = 80.74$). All mean fear scores were normally distributed (all $Ws(23) > 0.90$; all $ps > .10$). *T*-tests revealed significantly different fear scores for both conditions and all subgroups (all $ts(22) > |5.15|$, all $ps < .001$). In particular, fear was rated to be more pronounced in the negative condition compared to the neutral condition (negative condition: $M = 2.81$, $SD = 0.77$; neutral condition: $M = 1.15$, $SD = 0.54$), and most importantly, most pronounced in the *hesitating* subgroup, with the *hastening* subgroup showing more pronounced fear than the *neutral* subgroup (hesitating: $M = 3.56$, $SD = 0.54$; hastening: $M = 1.53$, $SD = 0.66$; neutral: $M = 1.15$, $SD = 0.54$).

Conclusion: The blind ratings are in line with the subdivision into the subgroups *hesitating*, *hastening*, and *neutral*, as proposed based on the investigators' assessment. All subgroups differed significantly in the fear levels as assessed by naive raters based on the participants' behavior. Consequently, participants' fear levels were explicitly and distinctly expressed in their behavior, even observable by blind, naive raters, indicating a high level of realistic fear behavior.

Statistical Analysis

All statistical analyses were carried out using SPSS 26 (IBM). All variables were tested for normal distribution regarding each group separately using the Shapiro-Wilk test and all further statistical tests were chosen accordingly (see **Supplementary Material S2** for a detailed report of the Shapiro-Wilk test). In case that at least one subgroup per variable or at least one subscale or subvariable of a measure was not normally distributed ($p < 0.1$), a non-parametric test (Kruskal-Wallis test, Mann-Whitney *U*-test) was used for the analysis of that measure, as parametric tests, i.e., ANOVA and *t*-test are less robust to violation of normal distribution in case of unequal group sizes.

Subjective Measures

The scales of the questionnaires were calculated as the sum of the corresponding item values (sum scale). Concerning the PANAS, in addition to the scores for positive and negative affect, the change in affect was calculated as the difference between pre-measurement and post-measurement (change = post–pre). For the in-house post-questionnaire, the subscales *affect* and *motivation* were calculated as mean values of the corresponding items. The preferred physical distance to either the werewolf or the sheep (*via* VAS) was transformed into the distance in percent (relative distance = preferred distance/total distance possible).

All questionnaires were analyzed using the Kruskal-Wallis test and complemented by post-hoc Mann-Whitney *U*-tests, with exception of the SSS-V, which was analyzed using a one-way ANOVA, complemented by post-hoc *t*-tests. Due to the directional wording of the hypothesis concerning acute fear and presence, negative affect, motivation, and presence were tested one-tailed. All other self-reports were tested two-tailed. Cronbach's *alpha* was calculated per scale and reached at least acceptable levels for most scales ($\alpha \geq 0.70$) with exception of the following subscales: BIS/BAS: goal drive, fun seeking, reward responsiveness; RST-PQ: reward interest, impulsivity; IPQ: Spatial presence, realness ($0.45 < \alpha < 0.70$, see **Supplementary Material S3** for details).

Dependent Measures

Exploration Time

Exploration time was compared between groups using the Kruskal-Wallis test, followed by post-hoc Mann-Whitney *U*-tests. Due to the directed hypothesis concerning exploration time, the total exploration time and the exploration time during epoch 57 (see **Figure 2**) were tested one-tailed.

Electroencephalic Measures

For statistical analysis of the FAAs, individual outliers were determined per epoch. Scores with a greater interquartile distance than 1.5 from the group mean were excluded from the analysis of the individual epoch. The FAA scores were analyzed based upon the subdivision of the *negative* condition into the subgroups "*hesitating*" and "*hastening*" and the *neutral* condition. The latter was not further subdivided (see results). The Kruskal-Wallis test was used for analysis and complemented by post-hoc Mann-Whitney *U*-tests. The parameter r ($\sqrt{\eta^2}$) was calculated as an estimate of effect size.

Cardiovascular Measures

The average change in rmSSD as a measure of HRV (delta = baseline 2—baseline 1) was compared between groups using the Kruskal-Wallis test and post-hoc Mann-Whitney *U*-tests. The parameter r ($\sqrt{\eta^2}$) was calculated as an estimate of effect size. Due to the directed hypothesis concerning HRV, the measure was tested one-tailed.

TABLE 1 | Test statistics for Mann-Whitney U-test regarding the subjective reports.

		Descriptive statistics			***Mann-Whitney U*-test**			
		n	***Md***	***SD***	***U***	***Z***	***P***	***effect size r***
RST-PQ: Impulsivity	Hesitating	33	17.00	3.52	225.00	−2.169	0.030*	0.17^{a}
	Hastening	21	19.00	2.79				
	Hesitating	33	17.00	3.52	308.50	−2.044	0.041*	0.26^{a}
	Neutral	27	19.00	4.16				
	Hastening	21	19.00	2.79	280.50	−0.063	0.95	0.01
	Neutral	27	19.00	4.16				
RST-PQ: Fight-Flight-Freeze-System	Hesitating	33	25.00	4.80	255.00	−1.627	0.104	0.22^{a}
	Hastening	21	21.00	5.98				
	Hesitating	33	25.00	4.80	278.50	−2.49	0.013*	0.32^{b}
	Neutral	27	22.00	5.30				
	Hastening	21	21.00	5.98	264.00	−0.406	0.684	0.06
	Neutral	27	22.00	5.30				
PANAS negative affect T2^{1}	Hesitating	33	14.00	5.17	290.50	−0.728	0.240^{1}	0.10^{a}
	Hastening	20	14.50	5.43				
	Hesitating	33	14.00	5.17	197.50	−3.406	0.001^{***1}	0.45^{a}
	Neutral	24	11.00	1.80				
	Hastening	20	14.50	5.43	155.00	−2.225	0.013^{*1}	0.34^{a}
	Neutral	24	11.00	1.80				
Change in negative affect^{1}	Hesitating	32	2.00	4.89	275.50	−0.840	0.205^{1}	0.11^{a}
	Hastening	24	1.50	4.74				
	Hesitating	32	2.00	4.89	189.00	−3.244	0.001^{***1}	0.43^{a}
	Neutral	24	−1.00	2.47				
	Hastening	24	1.50	4.74	141.00	−2.359	0.009^{*1}	0.34^{a}
	Neutral	24	−1.00	2.47				
Change in positive affect	Hesitating	32	4.50	5.86	273.500	−0.596	0.551	0.08
	Hastening	24	3.00	4.39				
	Hesitating	32	4.50	5.86	245.50	−2.299	0.021*	0.31^{a}
	Neutral	24	1.00	4.62				
	Hastening	24	3.00	4.39	152.00	−1.868	0.062	0.27^{a}
	Neutral	24	1.00	4.62				
In-house: affect^{1}	Hesitating	33	3.71	1.60	273.00	−1.306	0.096^{1}	0.20^{a}
	Hastening	21	4.00	1.83				
	Hesitating	33	3.71	1.60	34.50	−6.113	<0.001^{***1}	0.78^{b}
	Neutral	27	7.29	1.31				
	Hastening	21	4.00	1.83	75.00	−4.339	<0.001^{***1}	0.63^{b}
	Neutral	27	7.29	1.31				
In-house: motivation^{1}	Hesitating	33	3.25	1.82	235.00	−1.980	0.024^{*1}	0.30^{a}
	Hastening	21	4.50	1.96				
	Hesitating	33	3.25	1.82	95.00	−5.22	<0.001^{***1}	0.67^{b}
	Neutral	27	7.00	1.52				
	Hastening	21	4.50	1.96	128.50	−3.233	0.001^{***1}	0.47^{a}
	Neutral	27	7.00	1.52				
In-house: relative distance^{1}	Hesitating	30	0.74	0.29	264.5	−0.117	0.454^{1}	0.02
	Hastening	18	0.69	0.21				
	Hesitating	30	0.74	0.29	129.00	−4.41	<0.001^{***1}	0.58^{b}
	Neutral	27	0.22	0.27				
	Hastening	18	0.69	0.21	63.00	−4.172	<0.001^{***1}	0.62^{b}
	Neutral	27	0.22	0.27				
IPQ: spatial presece^{1}	Hesitating	33	8.00	3.71	249.00	−1.736	0.042^{1}	0.24^{a}
	Hastening	21	5.00	5.13				
	Hesitating	33	8.00	3.71	309.00	−2.033	0.021^{1}	0.26^{a}
	Neutral	27	6.00	6.20				
	Hastening	21	5.00	5.13	264.50	−0.396	0.346^{1}	0.06
	Neutral	27	6.00	6.20				

Note. *The detailed statistics for Kruskal-Wallis test are provided in* ***Supplementary Material S2****. The respective descriptive statistics are given per condition. The parameter* r ($\sqrt{\eta^2}$) *was provided as an estimate of effect size (a = small effect, b = medium effect, c = large effect). Significant differences between groups were marked accordingly (**$p < 0.05$; **$p \leq 0.01$, ***$p \leq 0.001$*). One-tailed tests are marked accordingly*^{1}.

RESULTS

Subjective Measures

No group differed significantly from others in personality traits that otherwise might have an impact on the perception of and reactions to the specific VR scenario, such as anxiety, empathy, paranormal belief, behavioral activation system, and behavioral inhibition system (all $Hs(2) < 5.10$, $p > 0.05$; see **Supplementary Material S2** for details), as well as sensation seeking ($F\ (2,74) = 3.05$, $p = 0.053$). However, groups differed in impulsivity ($H\ (2) = 6.23$, $p = 0.044$) and in the fight-flight-freeze system (FFF-S; $H\ (2) = 6.46$, $p = 0.040$) as assessed by RST-PQ. In particular, the *hesitating* group scored lower in impulsivity compared to the *hastening* and *neutral* groups. Moreover, the *hesitating* group scored significantly higher in the FFF-S compared to the *neutral* group. The difference in the FFF-S between the *hesitating* and *hastening* groups followed the same trend but did not reach significance. The *hastening* and *neutral* groups did not differ significantly in both traits (see **Table 1**).

Before the cave exploration, groups did not differ concerning their mood (all $Hs(2) < 1.1$, all $ps > 0.50$). However, after the cave exploration, groups reported different levels of negative affect, as well as differing changes in negative and positive affect. In detail, both *hesitating* and *hastening* groups experienced equal negative affect as well as similar increases in negative affect, but significantly stronger increases compared to the *neutral* group (see **Table 1**). Surprisingly, the *hesitating* group reported significantly higher increases in positive affect compared to the *neutral* group as well. The *hastening* group followed the same trend but did not reach significance. The *hastening* and the *hesitating* groups experienced similar increases of positive affect (see **Table 1**). All groups reported similar levels of presence (all $Hs(2) < 5.20$, all $ps > 0.07$), with exception of the sensation of *spatial presence* ($H\ (2) = 5.17$, $p = 0.038$)[1]. In particular, the *hesitating* group felt more spatially present compared to both other groups, whereas the *hastening* and the *neutral* groups exhibited similar levels of spatial presence (see **Table 1**).

As assessed by the in-house post-questionnaire, the *hastening* and the *hesitating* groups preferred a significantly greater distance to the werewolf, whereas the *neutral* group preferred a significantly closer distance to the sheep (22% of the possible distance). Descriptively, the *hesitating* group (74% of the possible distance) preferred a slightly greater distance to the werewolf compared to the *hastening* group (69% of the possible distance), but the groups did not differ significantly (see **Table 1**). Furthermore, both the *hesitating* group and the *hastening* group perceived the cave as strongly negative and reported a significantly greater motivation to leave the cave at an early stage compared to the *neutral* group. Even more, the *hesitating* group exhibited a significantly stronger motivation to leave the cave early compared to the *hastening* group. The *hastening* group perceived the cave as significantly more negative compared to the *neutral* group as well, and reported a high motivation to leave the cave early, whereas participants of the *neutral* group tended to perceive the cave as rather comfortable and were only slightly motivated to leave it at an early stage (see **Table 1**).

TABLE 2 | Test statistics for Kruskal-Wallis test regarding exploration time and HRV data.

	Kruskal-wallis test		
	H	***Df***	***P***
Total exploration time[1]	14.791	2	0.001***[1]
Exploration time epoch 57[1]	28.173	2	<0.001***[1]
HRV: Delta rmSSD[1]	2.003	2	0.184[1]

Note. *Significant differences between groups (*p < 0.05; **p ≤ 0.01, ***p ≤ 0.001) and one-tailed tests[1] were marked accordingly.*

Dependent Measures

Exploration time and Behavior

The *hesitating* group took approximately 1.7 times as long as the *hastening* group and the *neutral* group to reach the cave's exit and thus to end the exploration ($Md_{hesitating.} = 49.7s$; $Md_{hastening.} = 29.10$, $Md_{neutral.} = 33.15$). In contrast, the *hastening* and the *neutral* groups took approximately the same time to end the exploration (see **Tables 2**, **3**). This pattern was evident for epoch57, when participants headed towards the werewolf/sheep, as well (see **Table 2**, exploration time epoch 57). The *hesitating* group walked significantly slower towards the werewolf compared to the *hastening* group ($U = 81.00$, $z = -4.42$, $p < .001$[1], $r = 0.62$) and the *neutral* group towards the sheep ($U = 121.00$, $z = -4.52$, $p < .001$[1], $r = 0.60$), whereas *hastening* group and *neutral* group walked at the same pace ($U = 255.00$, $z = -0.11$, $p = .456$[1], $r = 0.02$). In detail, the *hesitating* group took more than three times as long as both other groups for this path section ($Md_{\text{hesitating}} = 21.57$; $Md_{\text{hastening}} = 6.60$; $Md_{\text{neutral}} = 6.09$; *Md* in seconds).

The significant difference in exploration time was reflected in the directly observable behavior within the cave: The *neutral* group explored the cave rather casually, maintaining a constant walking pace and showing no particular signs or verbalizations of unease. In contrast, both *negative* groups walked rather cautiously, looking around turn-offs before continuing the exploration. Both subgroups explicitly expressed fear by verbalizations and body language. For example, participants gasped, looked around nervously, or wrapped their arms protectively around themselves. Five participants terminated the experiment either at first sight of the cave's entrance area ($n = 1$) or at first sight of the werewolf ($n = 4$). Beyond that, the *hesitating* group either stopped or even hid behind the former wall when detecting the werewolf, whereas the *hastening* group did not hesitate at all, but advanced toward the werewolf to get past it (see data repository for exemplary video recordings). Based on these bodily fear cues, even naive raters were able to classify participants' fear levels adequately, indicating a high consistency with real-life fear behavior (see **Box 1**).

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[1] Measures of acute fear, i.e., negative affect and motivation to leave the cave as assessed via PANAS and the in-house post-questionnaire, as well as HRV and exploration time, were tested one-tailed due to directed hypotheses. All other hypotheses are tested two-tailed.

TABLE 3 | Test statistics for post-hoc Mann-Whitney U-test regarding exploration time.

		Descriptive statistics			*Mann-Whitney U*-test			
		N	*Md*	*SD*	*U*	*Z*	*p*	effect size *r*
Total exploration time^1	Hesitating	31	49.70	70.11	158.00	−2.932	0.002^{**1}	0.41^b
	Hastening	20	29.10	31.14				
	Hesitating	31	49.70	70.11	185.00	−3.49	$<0.001^{***1}$	0.46^b
	Neutral	26	33.15	22.77				
	Hastening	20	29.10	31.14	285.00	−0.044	0.483^1	0.01
	Neutral	26	33.15	22.77				

Note. *The respective descriptive statistics are given per group and the effect size r ($\sqrt{\eta^2}$; a = small effect, b = medium effect) was determined. Significant differences between groups (**p* < 0.05; **p ≤ 0.01, ***p ≤ 0.001) and one-tailed tests^1 were marked accordingly.*

Cardiovascular Measures

All groups exhibited equal changes in rmSSD between both baseline measurements (H (2) = 2.00, p = .184^1, see **Table 2**). Descriptively, all groups exhibited an increased rmSSD in the second baseline compared to the first baseline ($Md_{\text{hesitating}}$ = 13.58; $Md_{\text{hastening}}$ = 17.74; Md_{neutral} = 17.81), indicating higher stress levels during the first baseline.

Electroencephalographic Measures

The Kruskal-Wallis test revealed differences regarding the FAA scores between the three subgroups for epoch 34 (H (2) = 6.13, p = 0.047) and epoch 57 (H (2) = 6.59, p = 0.037). However, they did not differ during baseline or further epochs (all *Hs(2)* < 4.6; all *ps* > 0.10; see **Supplementary Material S2** for details).

Hence, only epoch 34 and epoch 57 were further analyzed by post-hoc Mann-Whitney *U*-tests. In epoch 34, a significantly stronger left frontal cortical activity was observed in the *hastening* group compared to the *neutral* group, which exhibited a stronger right frontal cortical activity (see **Table 4** and **Figure 3**). However, the *hesitating* group did not differ from the *hastening* group or from the *neutral* group with respect to their FAA scores. In contrast, the *hastening* and the *hesitating* groups differed significantly during epoch 57, with the *hesitating* group showing greater left frontal cortical activity and the *hastening* group showing greater right frontal cortical activity. Both did not differ significantly from the *neutral* group during this epoch (all *Us* > 240.00, all *ps* > 0.05, see **Table 4** and **Figure 3**).

DISCUSSION

The present study aimed to examine authentic fear responses, especially complex behavioral expressions of fear, and the electrophysiological correlates of approach and avoidance, i.e., frontal alpha asymmetries (FAA) in an immersive virtual reality setup. The incremental value of the study lies particularly in the simultaneous examination of realistic behavior and the associated electrophysiological responses. To this end, participants explored either a negative, i.e., frightful cave, containing corpses and a monstrous werewolf, or a neutral cave, containing tree trunks and a sheep. As expected, the negative cave elicited significantly stronger negative affect, fear, and the motivation to withdraw from the scenario earlier as opposed to the *neutral* condition. Going beyond previous findings, these affective responses were very pronounced and identifiably reflected in the participants' behavior. While the neutral condition's participants explored the cave rather casually, the *negative* condition's participants walked rather cautiously, adapting their pace to the threatening atmosphere. Even more, the *negative* condition exhibited two different behavior patterns, subdividing participants into a *hesitating* and a *hastening* group. Surprisingly, and even though self-reports and behavior indicated great differences in emotional experiences, the different groups could be distinguished in only two out of seven cave sections based on the FAAs.

Affective Responses to the Virtual Cave

In line with previous research, the respective design of the cave was sufficient to trigger distinct emotional reactions as intended. Indicative of successful fear elicitation, both negative subgroups reported higher levels of acute fear compared to the *neutral* condition. Specifically, both *negative* groups reported highly negative affect, a strong fear of the respective stimuli, and great motivation to leave the cave early, while the *neutral* group did not. With all negative stimuli removed, a still dimly lit cave exhibited no particular reports of fear in the *neutral* condition. Hence, while context and distinct cues determine which specific emotion is induced, i.e., fear of an approaching werewolf (Felnhofer et al., 2015; Lin, 2017), the level of interactivity adds to the plausibility and realness of the VE (*plausibility illusion*; Slater, 2009), thereby increasing emotional involvement (Gorini et al., 2010; Diemer et al., 2015) and behavioral realism (Blascovich et al., 2002; Slater, 2009; Kisker et al., 2019a). In particular, the possibility to interact with and within the VE, and to be personally affected by occurring events overcomes the remoteness of conventional screen experiences (Slater, 2009; Lin, 2017; Lin et al., 2018; Lin, 2020; Kisker et al., 2020; Schöne et al., 2019). More than that, the experienced self-efficacy may reinforce the feeling of personal vulnerability to the occurring events (see Lin, 2017; Lin et al., 2018).

In a similar vein, participants of all groups felt generally present within the VE. However, the *hesitating* group felt

TABLE 4 | Test statistics for Mann-Whitney U-test regarding the FAA scores during epoch 34 and epoch 57.

		Descriptive statistics			Mann-whitney U-test			
		n	*Md*	*SD*	*U*	*Z*	*p*	*effect size r*
Epoch 34	Hesitating	30	−0.07	0.35	236.00	−1.27	0.205	0.18^{a}
	Hastening	20	−0.21	0.39				
	Hesitating	30	−0.07	0.35	316.00	−1.42	0.155	0.19^{a}
	Neutral	27	0.08	0.41				
	Hastening	20	−0.21	0.39	158.00	−2.41	0.016*	0.35^{b}
	Neutral	27	0.08	0.41				
Epoch 57	Hesitating	31	−0.01	0.25	188.00	−2.35	0.019*	0.33^{b}
	Hastening	20	0.07	0.27				
	Hesitating	31	−0.01	0.25	282.00	−1.94	0.053	0.26^{a}
	Neutral	26	0.08	0.35				
	Hastening	20	0.07	0.27	241.00	−0.421	0.674	0.06
	Neutral	26	0.08	0.35				

Note. *Kruskal-Wallis test revealed no group differences concerning further epochs. Significant differences between groups as indicated by Mann-Whitney* U-*test are marked (**p < 0.05; **p *≤ 0.01,* ***p *≤ 0.001). The respective descriptive statistics are given per group and the effect size* r ($\sqrt{\eta^2}$*; a = small effect, b = medium effect) was determined. Positive FAA scores indicate withdrawal motivation, whereas negative FAA scores indicate approach motivation.*

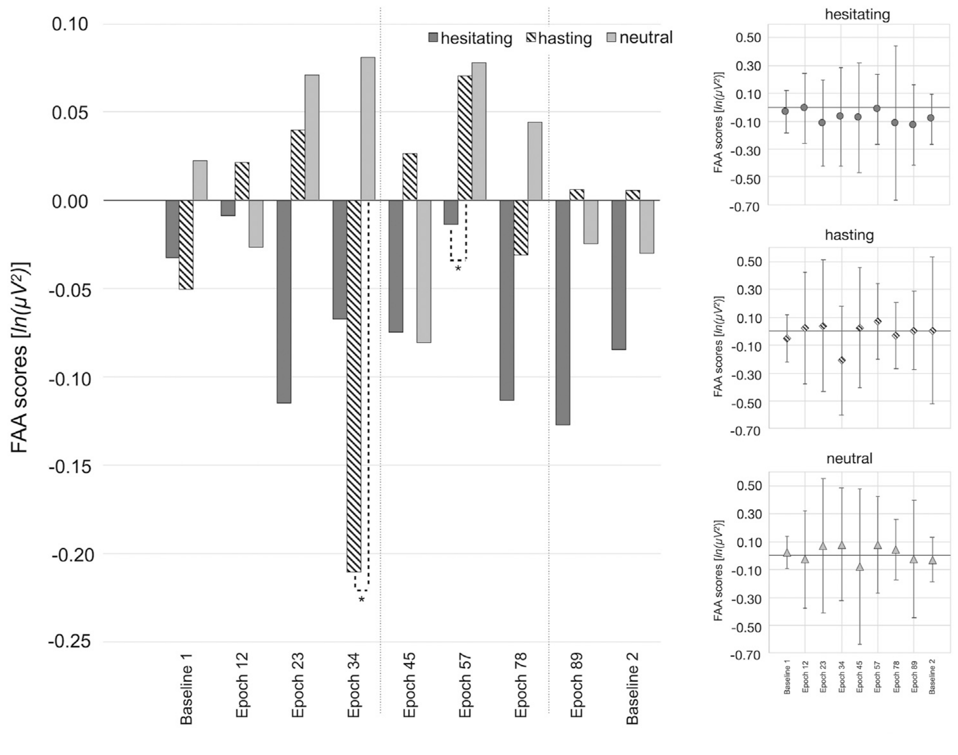

FIGURE 3 | FAA scores [ln (μV²)] per subgroup and epoch of the cave exploration. Significant differences between groups are marked (**p* <0.05; ***p* ≤ 0.01, ****p* ≤ 0.001). Positive FAA scores indicate relatively greater right frontal cortical activity, whereas negative FAA scores indicate relatively greater left frontal cortical activity. The standard deviations from group mean are depicted as error bars in separate panels for increased visibility. The area between both dotted grey lines indicate the epochs during which the creature (werewolf/sheep) was visible.

more spatially present compared to both other groups. Numerous previous studies indicate a positive correlation between emotion and the feeling of presence, although the effective direction remains unclear (e.g., Riva et al., 2007; Diemer et al., 2015; Felnhofer et al., 2015; Kisker et al., 2019a). As both conditions allowed for equal levels of interactivity, spatial presence might be enhanced by emotional arousal, as the *hesitating* group felt the most frightened being the cave. A previous mixed reality study also only modified the visual impression, i.e., threatening vs. non-threatening, and concluded that the threatening condition corresponded with higher sensations of presence (Kisker et al., 2019a). However, although these findings may seem intuitive, our data does not allow a causal conclusion and could also be the result of interdependence of emotional experience and presence (Kisker et al., 2019a). Moreover, all groups exhibited equal levels of general presence, involvement, and realness, opposing the idea of modulation of presence by the emotional experience alone. Accordingly, factors other than emotion and immersion may have varying effects on the dimensions of presence, which should be objective to further research.

Surprisingly, both *negative* groups experienced a stronger increase in positive affect compared to the *neutral* group. This might, at first sight, seem counterintuitive. However, previous studies also found an increase in positive affect after unpleasant situations, ascribing this finding to relief, or even pride about having mastered an unpleasant, or in our case threatening, situation (Williams and DeSteno, 2008; Kisker et al., 2019a). Contrary to our expectations, the groups did not differ in the extent to which their HRVs changed. This is surprising given that the HRV parameter rmSSD tends to decrease during stressful situations (Castaldo et al., 2015). Therefore, we had expected that both *negative* groups would show a significant reduction in rmSSD compared to the *neutral* group. Instead, all groups showed a slight, not significantly different increase in rmSSD after exploring the cave compared to pre-exploration measurement. The increase in rmSSD, classically interpreted as reduced stress experience (Castaldo et al., 2015), might nevertheless reflect the changes in positive affect: The uncertainty about the cave's content and size before its exploration might have led to anticipatory stress, while the completion of the exploration might be experienced as a relief. However, the recording of the pre- and post-exploration phases might not have been sufficient to validly determine HRV parameters. Although rmSSD can be determined based on short-time measurements, it is usually preceded by resting phases (Castaldo et al., 2015). In our experiment, participants moved physically between measurements, which may have distorted the HRV assessment and limits its interpretability.

As all groups were equal in prior VR-experience, pre-experimental mood, trait anxiety, and further personality traits right before the VR exposure, differences between groups during or after cave exploration cannot be traced back to pre-existing differences, but the cave exploration. As the only, but a highly interesting exception, the *hesitating* group reported significantly lower impulsivity than both other groups and scored higher on the FFF-S, which indicates that their behavior is more likely to be determined by avoidance tendencies (Corr and Cooper, 2016; Pugnaghi et al., 2018) and corresponds to their initial reaction when detecting the werewolf.

Authentic Fear Behavior in Immersive Virtual Reality

Most importantly, and going beyond matching self-reports, participants adapted their behavior immensely to their virtual surroundings. While the *neutral* group explored the cave rather casually, both *negative* groups exhibited distinct signs of acute and strong fear expressed via body language: They slowed down their pace, glimpsed around corners before taking the turn-off, or held their arms tight to their bodies in addition to verbal expressions of fear (see Adolphs, 2013). More than that, when being confronted with the werewolf, participants tended to advance toward the werewolf to get past it or to retreat, subdividing participants of the *negative* condition into two distinct subgroups: The *hesitating* group hesitated or even hid behind the former turn-off when detecting the werewolf, which corresponds to their lower levels of impulsiveness and more pronounced action control by avoidance. In contrast, the *hastening* group advanced toward the next turn-off before the werewolf approached any closer. These behavioral patterns were reflected in significantly higher exploration times in the *hesitating* group compared to both other groups. Slowing down their pace allows for greater vigilance and thus for potential hazards to be identified more quickly (Rinck et al., 2010). By hesitating to pass by the werewolf, the *hesitating* group stayed in the cave longer, whereas the *hastening* group, in comparison, abbreviated it by fleeing towards the cave's exit, thereby matching the *neutral* group's exploration time.

These behavioral adaptions point towards a crucial characteristic of VR setups: Since they are the subject of the virtual events and are personally involved in them (Slater, 2009; Slater and Wilbur, 1997; Kisker et al., 2020; Schöne et al., 2019), a behavior change is inevitable to deal with the threats within the cave (see Kisker et al., 2019a). The impression of realness must therefore have been so intense that the knowledge of being in a VR simulation was not sufficient to suppress the feeling of personal threat and a corresponding coping reaction (*place illusion;* Slater, 2009). As the mixed reality design allows for realistic sensorimotor actions, participants are enabled to react naturally and promptly when confronted with fear cues. In particular, realistic responses are enhanced by the impression of being directly and personally affected by the events within the VE (Slater and Wilbur, 1997; Nilsson, et al., 2016), for example the impression, that the werewolf can actually reach and harm them.

In standard laboratory settings, participants are supposed to indicate their natural response via substitutional responses: They are required to cognitively evaluate their initial response, determine the correct substitutional response, and then carry it out. In a real-life, threatening situation this chaining of cognitive evaluation and reaction might be dysfunctional. Rather, people would instinctively back off, freeze, or defend themselves physically as an initial impulse. Following LeDoux's (e.g. LeDoux, 1995; LeDoux, 1996; LeDoux, 1998; Debiec and LeDoux, 2004) theory on the fear circuit, VR setups would allow to access the immediate, emotional processing of stimuli. Conversely, capturing fear via substitutional responses would involve the slower cognitive path, as participants process their initial reaction and match it to an abstract, pre-set action to indicate how they feel. However, reactions triggered by VR events can only be accepted as equivalent to real reactions if virtual and real environments actually elicit identical reactions (Slater, 2009).

More and more studies indicate that VR settings not only lead to stronger emotional reactions compared to classical PC setups but that these reactions triggered by virtual events correspond to their real-life counterparts (Gorini et al., 2010; Higuera-Trujillo et al., 2017; Chirico and Gaggioli, 2019). Consequently, VR setups allow for a more naturalistic and non-mediated assessment of fear, offer an immense spectrum of response options, and involve the full body, mimicking the natural fear reaction to events in the real world (Bohil et al., 2011).

Alpha-Asymmetry Models and Complex Behavioral Responses

Remarkably, the electrophysiological response distinguished between subgroups in two of the seven exploration sections based on the FAA. Based on existing models, and equivalent to Rodrigues et al. (2018), we expected relatively stronger left-frontal activity for approach-related behavior, i.e., negative FAA-scores when the *hastening* group approached the werewolf, and a relatively stronger right-frontal activity for avoidance-related behavior, i.e., positive FAA-scores for the *hesitating* group. Neutral behavior was not proposed to be linked to a distinct asymmetry.

The three subgroups were distinguishable directly after passing the corpse/tree trunk and hearing the werewolf/sheep (epoch 34), and when walking towards the werewolf/sheep (epoch 57). In particular, the *hastening* group differed significantly from the *neutral* group in epoch 34, exhibiting relatively greater left frontal activity, indicating approach motivation, while the *neutral* group exhibited relatively greater right frontal activity, indicating avoidance motivation (e.g., Harmon-Jones and Gable, 2018; Rodrigues et al., 2018). The *hesitating* group, descriptively exhibiting a slight approach motivation, did not differ significantly from any of the other groups. One might argue that both *negative* groups exhibited approach motivation towards the exit. The *neutral* group had no incentive to leave the cave early and was thus, possibly motivated to avoid the exit to explore the situation longer.

Moreover, during epoch 57, the *hastening* and *hesitating* groups differed significantly, with the *hastening* group exhibiting avoidance motivation and the *hesitating* group exhibiting approach motivation. On the one hand, the *hastening* group's avoidance motivation might be linked to their instant initiation of an escape from the current cave section towards the exit before the werewolf comes any closer. The *hesitating* group's approach motivation, on the other hand, might reflect the emotional self-control to pass the werewolf to reach the exit after initially hiding or hesitating. The latter interpretation supports recent models that associated FAAs with inhibitory top-down regulation of emotion (Lacey et al., 2020; Schöne et al., 2015). The *neutral* group exhibited equal levels of avoidance motivation compared to the *hastening* group, which might indicate avoidance of leaving the cave early. However, during this epoch, none of the groups knew that the exit was behind the next turn. Therefore, the previous interpretation seems rather speculative.

In terms of the revised sensitivity theory (Gray and McNaughton, 2000), Wacker and colleagues (Wacker et al., 2003; Wacker et al., 2008) introduced the behavioral inhibition model of anterior asymmetry (BBMAA). The BBMAA relates relatively greater left frontal activity, as in the *hesitating* group, to the activation of the fight-flight-freeze-system (FFF-S), responding to negative stimuli and threat, whereas relatively greater right frontal activity, as in the *hastening* group, might relate to the behavioral inhibition system (r-BIS), allowing for superordinate emotion-regulation and behavioral control (Gray and McNaughton, 2000). According to the group's behavioral responses, hesitating and hiding from the werewolf would fit with the FFF-S and might, in line, be interpreted as active behavior to avoid the fear cue. Vice versa, accelerating their pace to instantly pass the werewolf would fit with the r-BIS. But notably, the respective asymmetry is proposed to indicate passive behavior (Wacker et al., 2003; Rodrigues et al., 2018), standing in stark contrast to instantly approaching the werewolf and passing it. To hasten past the werewolf is undoubtedly effective to escape the threatening situation and thus may be interpreted as avoidance rather than approach. However, the *hastening* group seems to be primarily driven by emotion regulation, as they do not hesitate, but instantly move towards the werewolf. Hence, the synthesis of this behavior and FAA might rather relate to effortful control of emotion (Lacey et al., 2020; Schöne et al., 2015), allowing to escape from the threatening situation instead of freezing.

None of the aforementioned explanatory approaches covers that the groups' FAAs did not differ significantly for the greater part of the cave exploration. Despite of showing such a variety of and strongly pronounced behavioral responses, participants of all groups could only be distinguished in two of the seven cave sections based on the FAA data. This was particularly surprising as the *negative* condition triggered intense negative affect, as well as a high motivation to leave the cave early, which was significantly reflected in self-reports and behavior. Walking towards a corpse and sounds of crying compared to a tree trunk and wind sounds were not accompanied by significantly different FAA scores between groups. Even more, the *hesitating* group descriptively exhibited relatively greater left frontal activity throughout the cave exploration which is, according to the most well-known models, associated with approach motivation or positive affect (e.g.,Davidson et al., 1990; Gable and Harmon-Jones, 2008; Harmon-Jones and Gable, 2018). For obvious reasons, the valence model (e.g., Davidson et al., 1990; Davidson, 1998) does not correspond to the observed behavioral responses, while one might speculate whether the observed approach motivation might reflect to urge to reach the exit.

Hence, the FAA data collected in our immersive VR setup could be aligned with previous models only to a very limited, inchoate degree. Although initial desktop-VR studies provided evidence that the behavioral patterns in a video game trigger FAAs corresponding to the motivational model (Rodrigues et al., 2018), we were unable to replicate these findings in a highly immersive VR setup.

The Special Role of Immersive Virtual Reality Setups

Even though we could not fully reconcile the self-reports and behavioral data with the obtained FAA data, we would like to consider the following points as potential, but not incontrovertible explanations for the observed discrepancies:

As previously speculated, the *hesitating* group exhibiting an approach motivation throughout the cave exploration might be attributed to having a strong motivation in terms of approaching the cave's exit. This assumption presupposes that FAAs do not reflect an emotional or motivational response to distinct fear cues, but a higher goal, supporting the idea that the FAA dynamics might reflect top-down inhibitory executive processes, rather than motivational tendencies *per se* (Schöne et al., 2015). In line, the neutral cave might elicit FAAs since the aim of finding the exit is pursued, although the neutral environment would not in itself provide a specific incentive to do so. However, as leaving the cave seems much more urgent in the *negative* condition, it would still have been expected that the FAAs elicited by the *neutral* and the *negative* conditions would be significantly different.

Apart from that, the best-known FAA models are not entirely consistent with each other: each model has been repeatedly lined with evidence, revised, or even overruled (for review see e.g., Harmon-Jones and Gable, 2018; Lacey et al., 2020). Considering this limited consistency, it is less surprising that the FAA data obtained from a very different setup compared to the conventional assessments does not match previous models one-to-one. In terms of emotion induction methods, the discrepancy might arise from the multidimensional nature of VR setups: a major advantage of classical laboratory experiments is the possibility to isolate relevant processes (Kvavilashvili and Ellis, 2004; Parsons, 2015). In contrast, VR setups, like real experiences, are multidimensional (Bohil et al., 2011; de la Rosa and Breidt, 2018; Pan and Hamilton, 2018) and, as we argued, facilitate realistic reactions (e.g., Blascovich et al., 2002; Slater, 2009; Kisker et al., 2019a). Accordingly, rather weak signals like the FAA may play in concert with further cognitive and emotional processes in complex, realistic situations (see Bohil et al., 2011). Thus, classical measurements as applied in conventional setups might not adequately capture FAAs under more naturalistic conditions and might need adaption for sufficient application.

In a similar vein, the assignment of FAAs to certain emotional or motivational states might not be unrestrictedly generalizable to complex behavioral reactions going beyond abstract responses: Models concerning the FAA are based on highly standardized laboratory setups, which strongly limit the behavioral response options to rather abstract stimuli presented on a screen (e.g., Wacker et al., 2008; Parsons, 2015). So-called desktop-VR settings, being somewhat more immersive, still reduce the behavioral response options, e.g., to movements of a joystick (e.g., Rodrigues et al., 2018; Brouwer et al., 2011). In contrast, immersive VR setups, such as the physical exploration of a cave, allow for multisensory, realistic sensations and significantly broader and non-mediated behavioral reactions (e.g., Rinck et al., 2010; Lin, 2017). Accordingly, the reduction of complex reactions to a single electrophysiological marker seems too abstract for realistic conditions (e.g., Lange and Osinsky, 2020; Bohil et al., 2011).

One might argue that movement-induced artifacts or wearing an HMD might overshadow significant differences between groups. However, recent methodological examinations demonstrated that mobile EEG obtains good data quality during walking even in single-trial setups (Debener et al., 2012; Nathan and Contreras-Vidal, 2016), and wearing common HMDs does not impact the EEG's signal quality regarding frequency bands below 50 Hz (Hertweck et al., 2019). Accordingly, it seems unlikely that differences between groups would have been overshadowed.

Summing up, the source of the discrepancy between behavioral responses and canonical FAA models is not yet conclusively understood. The differences found between groups seem to be mainly attributable to top-down emotion regulation (Lacey et al., 2020; Schöne et al., 2015). However, based on the aforementioned considerations, we assume that the canonical FAA and respective models cannot be applied to complex, holistic behavior without restriction or adaption, as FAAs have so far been investigated by means of abstract responses. Rather, the complexity of realistic behavioral responses may not be fully predicted by a single, very specific electrophysiological marker (Bohil et al., 2011; Lange and Osinsky, 2020). Accordingly, contemporary FAA models offer an avenue to explore approach and avoidance behavior, but under realistic conditions, FAAs may not be as predominant as previous models suggest.

Ethical Challenges of Using VR as an Experimental Tool

With the high level of realism that VR offers, the ethical and moral responsibility in the implementation of experimental studies increases at an exponential rate. Many objectives could potentially be investigated more naturally and efficiently when implemented via realistic experimental setups. Nevertheless, the participants' safety must always come first, and it must be carefully considered whether the gain from extended knowledge justifies the participants' potential strain.

Despite ethical approval, exploring an unknown cave without warning that, and which negative stimuli would await the participants was a significant strain on them. Five of the 59 participants exploring the negative cave terminated the experiment at the first sight of either the cave's entrance (n = 1) or the werewolf (n = 4). Although being anecdotal evidence only, some participants whimpered heavily, others engaged in self-calming strategies, like telling themselves repeatedly that it was only a game to break immersion. One participant even started crying when detecting the werewolf, three participants reported having nightmares the night after the experiment. To put it bluntly, we were rather surprised that so many participants completed the cave exploration while experiencing intense fear and distress, although they were distinctly and repeatedly instructed that they could stop the experiment immediately if they felt uncomfortable.

Some VR horror games even explicitly warn that the experience in VR is more intense compared to conventional games and might cause significant psychological strain. Attending and staying in such simulations could be attributed to the general appeal of mediated horror content (Lin et al., 2018). Considering that VR setups are assumed to evoke real-life behavior (e.g., Slater, 2009; Kisker et al., 2019a), emotions (e.g., Higuera-Trujillo et al., 2017; Chirico and Gaggioli, 2019), and transfer such experiences to real-life in terms of learning (e.g., Ragan et al., 2010) and mnemonic processes (e.g., Kisker et al., 2019b; Schöne et al., 2019; Kisker et al., 2020), it is an effective tool for e.g., exposure therapy (for review see e.g., Botella et al., 2017). But on the flip side of this coin, VR has not only the potential to treat but also to cause psychological dysfunction, such as PTSD-related symptoms (e.g., Dibbets and Schulte-Ostermann, 2015). The blurring of the mental border between virtual and real, and the resulting costs and benefits for all parties involved, must therefore be weighed very carefully on a case-by-case basis (for an in-depth discussion of ethics of virtual reality see e.g., Parsons, 2019; Slater et al., 2020).

CONCLUSION

Our results demonstrate that the employed VR setup facilitates realistic fear responses beyond affective responses: Exceeding the participants' self-reports of intense fear in both *negative* subgroups, they adapted their behavior to the encountered situation. While conventional setups can only operationalize the participants' substitutional response, e.g., in the form of a keystroke, VR setups allow for an immediate expression and assessment of the comprehensive fear response, e.g., by physically backing away from a stimulus. To our best knowledge, this study is the first one to investigate complex behavioral fear responses employing a mixed VR setup and thus, complements previous findings. Participants exploring the negative cave either quickly advanced toward the werewolf to get past it or retreated when spotting the werewolf. In stark contrast, participants exploring the neutral cave behaved casually and showed no particular signs of fear or discomfort. Overall, these behavioral responses exhibited in the cave resemble lifelike responses on an affective but foremost on the behavioral level, extending scientific evidence for VR-based research's feasibility and effectiveness.

Moreover, no previous study has collected electrophysiological correlates of approach and avoidance under similarly immersive conditions. The different behavioral patterns were reflected in the electrophysiological responses. Specifically, the FAA discriminated between the advancing (*hastening* group) and retreating (*hesitating* group) behavior as they walked towards the werewolf in the *negative* condition, indicative of differences in emotion regulation. Furthermore, differences between the *hastening* and the *neutral* groups were obtained only at rare occasions. Especially the absence of effects is remarkable, and albeit their ability to discriminate between different motivational or affective states, the remaining FAAs could not be reconciled with contemporary FAA models. This discrepancy could be attributed to the FAA models being based on data obtained under abstract laboratory conditions. The study at hand further incorporates the participants' complex behavioral responses, possibly affecting motivational tendencies.

Hence, putting laboratory-based models to the test under realistic conditions shows that they may not unrestrictedly predict real-life behavior. Yet, they provide a baseline for further refinement of experimental findings, which can be complemented by VR-based research. Accordingly, our findings demonstrate the high potential of implementing VR technology in experimental settings to increase the ecological validity of scientific findings. VR allows for non-mediated and life-like affective and behavioral responses and scientific measurements of real-world processes.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://osf.io/jwt7d/?view_only=92bda76c430247bca3a93eacf4567813

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the local ethic committee of Osnabrueck University, Germany. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

The study is based on a concept drafted by BS. All authors contributed to the study design. KF, MK, FT, PO, and NL developed the Unity VR environment and the physical replica under supervision of BS and JK. JK and LL integrated EEG and ECG applications into the Unity environment. Testing and data collection were performed by JK, LL, and KF. CG developed the application "Cagliostro" for the video rating of the participant's behavior. Data analyses were performed by JK under the supervision of BS and TG. JK and LL performed the data interpretation under the supervision of BS, TG, and RO. JK drafted the manuscript, LL revised the manuscript. BS, TG, and RO provided critical revisions. All authors approved the final version of the manuscript for submission.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2021.716318/full#supplementary-material

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2.3 Study 3: *Virtual reality experiences promote autobiographical retrieval mechanisms: Electrophysiological correlates of laboratory and virtual experiences*

Abstract

Recent advancements in memory research indicate that virtual reality (VR) experiences are more vividly memorized as compared to conventional laboratory events. In contrast to the latter, VR experiences are highly immersive, simulating the multimodality, vividness and inclusiveness of real-life experiences. Therefore, VR might enable researchers to identify memory processes underlying events which participants have actually experienced, in contrast to conventional on-screen experiences. To differentiate the electrophysiological correlates of memory processes underlying VR experiences as compared to conventional laboratory experiences, participants watched videos either in a PC condition or in a VR condition, followed by an unannounced recognition memory test. As hypothesized, we replicated the well-established theta old/new effect for the PC condition, but remarkably, this effect was absent in the VR condition. Additionally, the latter was accompanied by significantly lower alpha activity as compared to the PC condition. As increases in theta-band responses are related to top-down control on, and memory load during retrieval, the observed theta responses might rather relate to retrieval effort than to retrieval success per se. Congruently, higher alpha activity measured over occipital sensor areas in the PC condition reflect visually guided search processes within episodic memory. The VR condition comes in with lower alpha activity, reflecting immediate and effortless memory access. Hence, our findings indicate that the retrieval of VR experiences promotes autobiographical retrieval mechanisms, whereas recalling conventional laboratory events comes in with higher effort, which might not reflect the mechanisms of everyday memory.

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ORIGINAL ARTICLE

Virtual reality experiences promote autobiographical retrieval mechanisms: Electrophysiological correlates of laboratory and virtual experiences

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Abstract

Recent advancements in memory research indicate that virtual reality (VR) experiences are more vividly memorized as compared to conventional laboratory events. In contrast to the latter, VR experiences are highly immersive, simulating the multimodality, vividness and inclusiveness of real-life experiences. Therefore, VR might enable researchers to identify memory processes underlying events which participants have actually experienced, in contrast to conventional on-screen experiences. To differentiate the electrophysiological correlates of memory processes underlying VR experiences as compared to conventional laboratory experiences, participants watched videos either in a PC condition or in a VR condition, followed by an unannounced recognition memory test. As hypothesized, we replicated the well-established theta old/new effect for the PC condition, but remarkably, this effect was absent in the VR condition. Additionally, the latter was accompanied by significantly lower alpha activity as compared to the PC condition. As increases in theta-band responses are related to top-down control on, and memory load during retrieval, the observed theta responses might rather relate to retrieval effort than to retrieval success per se. Congruently, higher alpha activity measured over occipital sensor areas in the PC condition reflect visually guided search processes within episodic memory. The VR condition comes in with lower alpha activity, reflecting immediate and effortless memory access. Hence, our findings indicate that the retrieval of VR experiences promotes autobiographical retrieval mechanisms, whereas recalling conventional laboratory events comes in with higher effort, which might not reflect the mechanisms of everyday memory.

Introduction

How people behave in everyday life strongly depends on previous experiences either with a particular situation or personal general knowledge, e.g. concerning the realization of own goals, acting effectively and relating to other peoples (see Conway, 2005). This kind of information is predominantly encoded in and retrieved from autobiographical memory (AM). Similar to episodic memory (EM), autobiographical engrams encode personally experienced events in their respective spatial and temporal context (Tulving, 1983). Extending well beyond EM, AM encompasses highly self-relevant information, especially beliefs and knowledge about the self, experienced events and their relevance (see e.g. Conway, 2005; Greenberg & Rubin, 2003). Hence, AM comprises episodic engrams, extending it by self-referential and emotional processes. The retrieval of autobiographical memories is therefore not limited to temporal, spatial or contextual information, but bears great personal significance (Svoboda, McKinnon, & Levine, 2006). The retrieval of such everyday memories promotes the re-experience of the associated emotions (Svoboda et al., 2006), coming in with vivid and conscious reliving, and foremost the belief that they have actually occurred (Rubin, Schrauf & Greenberg 2003; Greenberg & Rubin, 2003).

While it is common practice to investigate everyday memory in the laboratory using paradigms that induce micro-events prior to recognition memory tests (see Cabeza et al., 2004), these settings are often criticized for lacking the complexity and variety of stimuli and response options

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characteristic to real-life experiences (Pan & Hamilton, 2018; Kvavilashvili & Ellis, 2004). Specifically, self-relevance and self-involvement are rarely realized in laboratory settings (see e.g. McDermott, Szpunar, & Christ, 2009). Obviously, such traditional approaches face a trade-off between high experimental control and ecological validity, i.e. the validity of the results obtained in the laboratory and generalized to everyday life (see Parsons, 2015).

Potentially overcoming this gap between experimental control and ecological validity, virtual reality (VR) has gained interest as a methodical tool in psychological research (see e.g. Parsons, 2015; Pan & Hamilton, 2018; Schöne et al., 2017, Kisker, Gruber, & Schöne 2019a, b). For memory research, VR experiences might provide a closer approximation to real-life experiences as compared to conventional laboratory settings. The former is characterized by a high level of sensory cues and thus, by high fidelity of the represented environment (Dan & Reiner, 2017). Accordingly, VR environments are more pronounced regarding vividness as compared to classical setups (Slater & Wilbur, 1997), which is also characteristic for AM (Greenberg & Rubin, 2003). In particular, everyday experiences arise from the complex, multisensory 3D-environment of the real world, while laboratory memories are generated by highly controlled events rather poor in sensory information (Cabeza & St Jaques, 2007). Moreover, the formation of such memories is accompanied by intuitive and quick monitoring and closely linked to self-referential processing (Moscovitch & Winocur, 2002; Cabeza & St Jaques, 2007). Importantly, the latter is as well increased under VR conditions due to its immersive character: VR facilitates an increased sense of presence, i.e. the subjective feeling of being within a virtual environment (VE; e.g. Slater & Wilbur, 1997; Schubert et al., 2001; Nilsson, Nordahl, & Serafin, 2016). Whereas immersion predominantly determines the degree to which the user is isolated from his physical surroundings by technical factors, like 3D-360° view and proprioceptive matching, presence promotes the subjective feeling of actually being in and acting within the VE (Slater & Wilbur, 1997; Nilsson, et al., 2016). Consequently, the sensation of acting within the VE comes in with the impression of being subject to the consequences of these actions and events in the VE (Slater & Wilbur, 1997; Nilsson, et al., 2016). For example, participant behave as if being in real danger when exposed to dangerous situations in an immersive VE, even though their surroundings could not physically harm them (e.g. Kisker et al., 2019a; Krijn et al., 2004; Gromer et al., 2019). In line, VR setups have been found to elicit the same emotional and physical reactions as compared to their real-life equivalents (Gorini et al., 2010; Higuera-Trujillo et al., 2017). Given this impression of mutual interaction with the virtual surroundings, VR experiences are more personally and emotionally relevant than mere on-screen experiences (see Kisker et al., 2019a; Schöne et al., 2016, Schöne et al. 2019). Hence, VR might improve the possibilities to investigate the mechanisms underlying real-life memory (see Parsons, 2015; Serino & Repetto, 2018; Schöne et al., 2016, Schöne et al. 2019; Kisker et al., 2019b; Burgess et al., 2001).

Initial studies of memory processes under immersive VR conditions found that retrieval of VR experiences is not only enhanced compared to the retrieval of conventional laboratory micro-events (see e.g. Serino & Repetto, 2018; Smith, 2019; Schöne et al., 2016, Schöne et al. 2019; Krokos, Plaisant, & Varshney, 2019; Ernstsen, Mallam & Nazir, 2019; Harman, Joel, Brown, Ross & Johnson, 2017), but also provides a closer approximation to real-life memory processes (Schöne et al., 2016; Schöne et al. 2019; Kisker et al., 2019b). In particular, a previous study found evidence that immersive VR experiences become part of an extensive autobiographical associative network, whereas conventional video experiences remain an isolated episodic event (Schöne et al., 2019). Going one step further, the retrieval of VR experiences is proposed to mainly rely on recollection, i.e. vivid and accurate remembering of events (e.g. Atkinson & Juola, 1973; Jacoby & Dallas, 1981) which is associated with AM (Roediger & Marsh, 2003; Conway, 2005). In contrast, retrieval of memories induced by conventional laboratory settings predominantly fall back on familiarity-based mnemonic processes (Kisker et al., 2019b), characterized as a subjective, vague feeling to remember a previous experience (e.g. Curran & Hancock, 2007; Rugg & Curran, 2007). Although both groups principally employed both, familiarity and recollection as non-exclusive retrieval mechanisms (see Jones and Jacoby, 2001), one mechanism predominated over the other as a function of the encoding context. Accordingly, encoding in VR resulted in a more precise and vivid retrieval than encoding the same scenario in a PC setup (Kisker et al., 2019b).

Overall, these studies suggest that VR experiences are not just observed, i.e. passively watching stimuli presented on a screen, but experienced in a self-relevant manner. Even interactive PC setups designed as immersive as possible by means of active exploration of a desktop-based environment, generate overall rather superficial engrams compared to exactly the same VE explored as a VR experience (Kisker et al., 2019b). Unlike conventional laboratory experiences, the latter become part of a personal experience like real-life experiences would (Schöne et al., 2016, 2019).

However, while the electrophysiological correlates of, for example, the sense of presence (e.g. Bouchard et al., 2009) and spatial memory (e.g. Rauchs et al., 2008) are recently more widely investigated, findings regarding the electrophysiological correlates of retrieval of episodic and autobiographical engrams encoded within VR are still rare (cf. e.g. Smith, 2019; Serino & Repetto, 2018; Plancher & Polino, 2017; Bohil et al., 2011). Accordingly, it is the aim of our study to differentiate the electrophysiological correlates of the retrieval of VR experiences as opposed to conventional laboratory experiences. Specifically, we examined a well-established electrophysiological marker of recognition memory tasks by means of the theta old/new effect obtained from laboratory settings (for review see Nyhus & Curran 2010; Guderian & Düzel, 2005; Hsieh & Ranganath, 2014; see also Gruber, Tsivilis, Giabbiconi & Müller, 2008; Klimesch et al., 1997a, 2001a). Therefore, we examined theta-oscillations (~ 4-8 Hz; e.g. Nyhus & Curran, 2010), which are most prominent at sensors over frontal-midline regions (e.g. Hsieh & Raganath, 2014). There is broad and stable consensus, that a characteristic theta-band synchronization can be observed in these regions in response to the retrieval of old stimuli, which are correctly remembered, i.e. in response to retrieval success. In contrast, new stimuli are associated with theta-band desynchronization (e.g. Nyhus & Curran, 2010). This effect was observed both subsequent to the stimulus presentation (e.g. Klimesch et al., 1997b; Klimesch et al., 2001a) and after a physical response of participants, e.g. key pressure (Gruber, Tsivilis, Giabbiconi, & Müller, Gruber et al., 2008). Moreover, theta-oscillations are associated with recollection of personal events (Guderian & Düzel, 2005) and hippocampal projections to neocortical frontal regions are regarded as possible generators of these oscillations during memory tasks (e.g. Hsieh & Ranganath, 2014). In conjunction with the characteristic frontal-midline theta-band synchronization, a decrease of the alpha-band response (~ 8–13 Hz, e.g. Berger, 1929) can regularly be observed during memory recall (e.g. Klimesch, et al., 1997b; Sauseng et al., 2009; Jacobs, Hwang, Curran & Kahana, 2006). This decrease of alpha-band response is regarded a reflection of visual processing (Clayton, Yeung & Cohen Kadosh, 2018), attentional processes (Klimesch et al., 1997a) and memory load (Sauseng et al., 2009; Jacobs et al., 2006; Jensen & Tesche, 2002; Dan & Reiner, 2017). In short, the theta-band synchronizes in response to mental activity, whilst the alpha-band desynchronizes (Berger, 1929 as cited in Klimesch et al., Klimesch, Doppelmayr, Schimke, et al. 1997b).

To examine whether this well-established and robust effect occurs under VR conditions as well, we set up an experiment in which participants incidentally encoded either immersive 3D-360° videos or conventional 2D videos followed by an unannounced recognition memory test. We assume that the VR condition will result in a higher sense of presence, better memory performance and higher accuracy of memory judgements as compared to the conventional PC condition. Moreover, we hypothesize to replicate the theta old/new effect for the conventional PC condition, manifested significant difference between theta-band responses to old and new stimuli, including a synchronization for old, and a desynchronization for new stimuli (see e.g. Gruber et al., 2008; Klimesch et al., 1997a, 2001a, b). In line, the alpha-band response should significantly decrease for new pictures as compared to old pictures. Concerning the VR condition, different outcomes might be possible: Under the premise that the theta old/new effect is exclusively linked to successful memory retrieval, theta-band synchronization for old stimuli should be higher for the VR condition as compared to the PC condition, as most studies indicate that VR setups enhance memory performance (e.g. Schöne et al. 2016, 2019; Smith, 2019) and activate recollection-based engrams (Kisker et al., 2019b). For the alpha-band, a similar pattern of results might be expected. However, as theta-band oscillations are related to further memory-related processes, e.g. memory load (Nyhus & Curran, 2010; Jensen & Tesche, 2002), decision making (Nyhus & Curran, 2010) and working memory (Hsieh & Ranganath, 2014), another outcome than the classical effect might be equally likely in the VR condition.

Methods

Participants

45 participants were recruited from Osnabrück University. The sample size was determined on the basis of previous studies with a similar study design (*cf.* Schöne et al., 2019; Kisker et al., 2019a). All participants were screened for psychological and neurological disorders and had normal or corrected-to-normal sight. Three participants were excluded during the anamnesis. When vision correction was necessary, only those participants who had contact lenses could participate, not those who wore glasses. It was ensured that the participants saw sharply on the screen as well as on the head-mounted display. Previous experience with VR environments was documented. All participants gave informed consent and were blind to the research question. The participants received either partial course credits or 15€ for participation.

The participants were randomly assigned to both conditions (VR vs. PC). Three participants were excluded from analysis due to insufficient data quality ($n=2$) and prior knowledge of the stimulus material used for the unannounced recognition memory test ($n=1$). After exclusion, we obtained 39 complete datasets for analysis (VR group: $n_{\mathrm{VR}}=20$, M_{age}=21.95, $\mathrm{SD}_{\mathrm{age}}=3.19$, 15 female, 19 right-handed; PC group: $n_{\mathrm{PC}}=19$, M_{age}=22.16, $\mathrm{SD}_{\mathrm{age}}$=2.32, 13 female, 18 right-handed).

Encoding

Stimulus material

One hundred 3D-360° videos from the Library for Universal Virtual Reality Experiments (luVRe, Schöne, Kisker, Sylvester, Radtke & Gruber, 2020; https://www.psycho.uni-osnabrueck.de/fachgebiete/allgemeine_psychologie_i/luvre.html) were used as stimulus material. All videos were recorded with the *Insta360Pro* VR-camera with a frame rate of 60 fps and 4 k resolution. Each video was 10 s long. The videos were randomly subdivided into targets and distractors for the unannounced recognition memory test in a 50:50 ratio. The themes of the videos were balanced between target and distractor videos (e.g. nature footage, interiors, medical facilities, sport events, social events; see supplementary material for a detailed description of the video content). Only the target videos were presented during incidental learning. Distractor videos were unknown to the participants and only used for the unannounced recognition memory test.

Procedure

Participants were randomly assigned to the VR- or the PC-condition. For the VR-condition, participants were equipped with a wireless version of the *HTC Vive Pro* head-mounted display. Video footage and sound were presented in 3D-360°, with a resolution of 1080 × 1200 pixels per display. Participants were allowed to look around, but not to turn 180° or walk around.

For the PC-condition, participants were seated in front of a curved monitor (35″, 90 cm screen diagonal, 37 cm height). The participant's distance to the screen was kept constant at 80 cm. The videos were presented in 2D videos in full-screen resolution. Sound was presented over standard speakers placed on both sides of the monitor.

For both conditions, the videos were presented in randomized sequences with the *GoPro VR Player,* providing the same video resolution for both conditions (cf. stimuli). Each randomized sequence was presented to one participant per condition. Each video was preceded by one-second fixation on a fixation cross. To facilitate incidental encoding, the presentation of each video clip was followed by a rating (10 s) as a distraction task (cf. Fig. 1). Participants were instructed to separately rate the experienced valence, arousal and motivation, i.e. their desire to stay in or leave the presented scene for each video separately on a scale from one (bad/not at all) to six (good/very much; cf. Kuhr et al., 2015). The ratings were consecutively presented on the (virtual) screen for 3.33 s each. The participants were familiarized with the rating before the video presentation. To guarantee for similar visual experience during the rating and maintain immersion, the rating took place in an exact virtual simulation of the laboratory in which the study actually took place, implemented as a 3D-360° video recording of the laboratory. In addition, the rating scales were displayed on the (virtual) monitor during rating phase. For the PC group, the simulation of the laboratory was displayed as a 2D video as well. The participant's answers were recorded with a dictation device. The ratings regarding valence, arousal and motivation of the videos were collected for the validation of a database and will not be further analyzed in this study. The presentation of the videos took a total of 19 min. To enhance immersion, all test leaders left the lab until the end of the video presentation. The participant was given a bell to

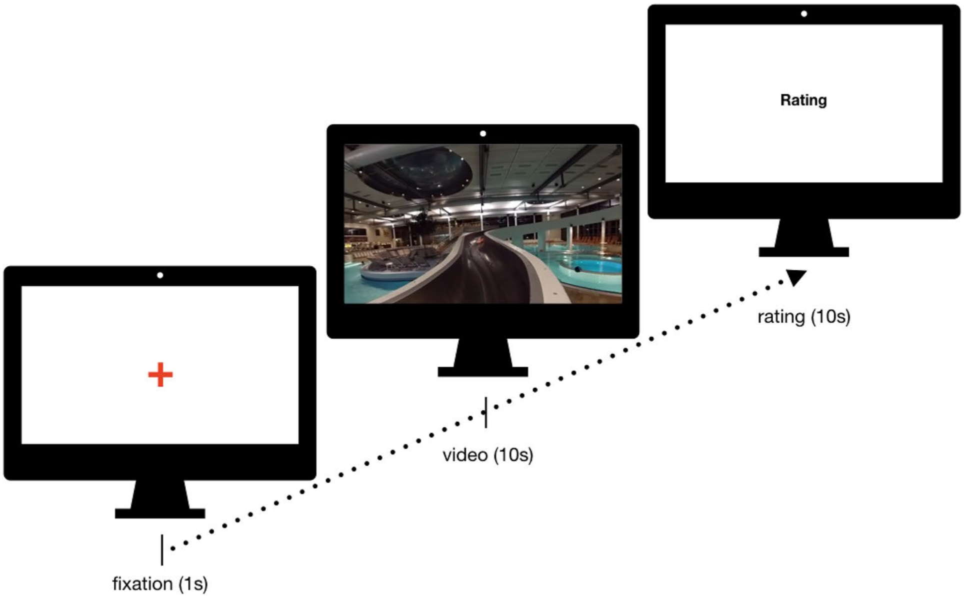


Fig. 1 Procedure of incidental encoding. Each of the 50 target videos was preceded by a fixation on a virtual screen and followed by the rating of valence, arousal and motivation. Each scale was faded in on the virtual screen separately for 3.33 s. During fixation and rating, a 3D-360° image of the laboratory in which the participants were actually located was presented

alert the test leaders if they wanted to quit the experiment early or felt uncomfortable.

To determine the sense of presence, participants were asked to fill in the German version of the *Igroup Presence Questionnaire* (*IPQ*; Schubert, Friedmann & Regenbrecht, 2001) and were asked for their experience of physical symptoms (vertigo, nausea). In addition, the participants were instructed not to discuss the videos with the test leaders until the end of the experiment.

Unannounced recognition memory test

Stimulus material

Monoscopic screenshots from both, distractors (referred to as new pictures) and targets (referred to as old pictures), were used as stimulus material for the unannounced recognition memory test. Per video, one representative screenshot was utilized as stimulus, resulting in 100 trials. The stimuli were presented on a conventional 24″ monitor with a parafoveal visual angle of 2 × 5°.

Procedure

The retention interval was set to 1 h during which the EEG was applied. If the participants mentioned the videos they had seen during encoding, they were kindly interrupted and asked not to discuss the videos until the end of the experiment. Participants were instructed about their task immediately before the unannounced recognition memory test.

The unannounced recognition test comprised of 100 trials. Per trial, participants had to indicate as fast as possible whether they recognized the presented stimulus as (1) definitely unknown, (2) rather unknown, (3) familiar or (4) vividly remembered (cf. Kisker et al., 2019b). Each trial started with randomly 0.5–0.8 s fixation, followed by 1.5 s presentation of the stimulus. The rating scale was then displayed until the participants responded via key pressure. The interstimulus interval lasted randomly between 1.0 s and 1.5 s (see Fig. 2). The response options were defined during instruction as follows (translated from German):

(1) Definitely unknown: I'm sure I've not seen this place
(2) Rather unknown: I guess I haven't seen this place
(3) Familiar: This place looks familiar to me
(4) Vividly remembered: I remember this place precisely and vividly.

Electrophysiological recordings and preprocessing

An electroencephalogram (EEG) with 128 electrodes, attached in accordance with the international 10-20-system was recorded for the duration of the unannounced recognition memory test. The Active-Two amplifier system from BioSemi (Amsterdam, Netherlands) was used. The sampling rate was 1024 Hz, the bandwidth (3 dB) 104 Hz. Additionally, horizontal electrooculogram (hEOG) and vertical electrooculogram (vEOG) were recorded and a common mode sense (CMS) and a driven right leg (DRL) electrode were applied. The EEG was recorded on the investigators' computer using ActiView702 Lores.

EEG data were analyzed using MATLAB. For further off-line analysis, the average reference was used. The EEG was segmented to obtain epochs starting 500 ms prior and 1500 ms following stimulus onset (baseline − 300 to − 100 ms). Artifact correction was performed by means of ''statistical correction of artifacts in dense array studies'' (SCADS; Junghöfer, Elbert, Tucker, & Rockstroh, 2000). In brief, this procedure uses a combination of trial rejection and channel approximation based

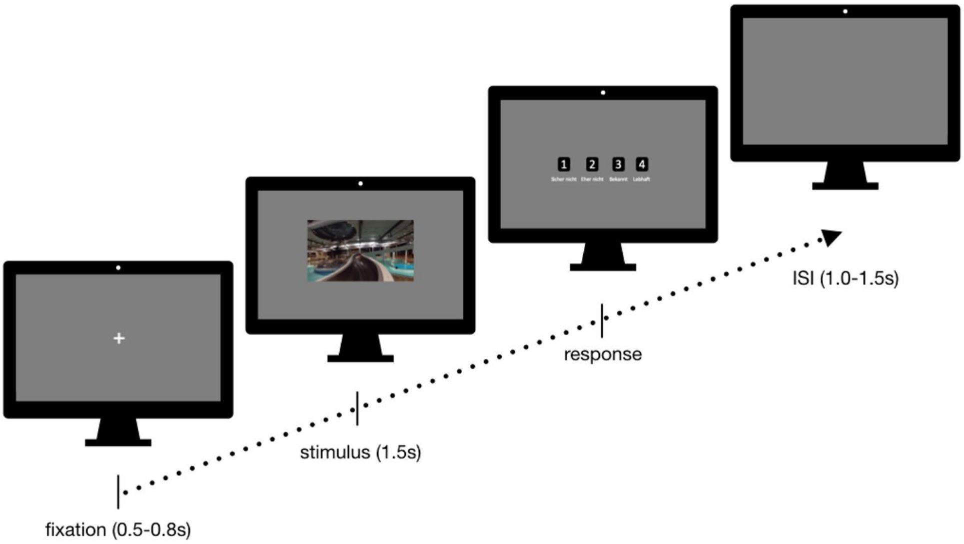


Fig. 2 Setup of the memory test trials: 0.5–0.8 s fixation, 1.5 s stimulus presentation, presentation of the scale until the participant's response, 1.0–1.5 s inter stimulus interval (ISI). Participants were asked not to blink from fixation until the response scale appeared

on statistical parameters of the data. For each trial, contaminated electrodes are detected based on a threshold criterion derived from the distribution of the amplitude, standard deviation, and gradient of the sensor across all trials. The information of these electrodes is replaced with a spherical interpolation from the full channel set. The limit for the number of approximated channels was set to 20. Epochs containing more than 20 channels with artifacts were rejected.

For demonstrating a robust signal at the frequency bands of interest, we first calculated a conventional fast Fourier transform (FFT, see Fig. 5) per trial and averaged across all electrodes, conditions and participants.

For further analyses and a comparison between experimental conditions, we considered it advantageous to take the signal's temporal evolution into account. Thus, for the subsequent examinations, spectral changes in oscillatory activity were analysed by means of Morlet wavelets with a width of 12 cycles per wavelet which is described in detail elsewhere (e.g., Tallon-Baudry & Bertrand, 1999; Bertrand & Pantev, 1994). In brief, the method provides a time-varying magnitude of the signal in each frequency band, leading to a time-by-frequency (TF) representation of the data. Due to the fact that induced oscillatory activity occurs with a jitter in latency from one trial to another (Eckhorn et al., 1990), they tend to cancel out in the averaged evoked potential. Thus, TF amplitude is averaged across single-trial frequency transformations, allowing one to analyze non-phase-locked components. Furthermore, because we focused on the non-phase-locked components of the signal, the evoked response (i.e., the ERP) was subtracted from each trial before frequency decomposition (for details, see Busch, Herrmann, Müller, Lenz, & Gruber, 2006). Given our interest in the lower-frequency range, we used wavelets from 0.25 Hz to 30 Hz.

Based upon prior literature (e.g. Nyhus & Curran, 2010) and our hypothesis, the frequency range from 4-7 Hz was included in the analyses and checked against visual inspection of the FFT (see Fig. 5). However, visual inspection of the FFT revealed high power for 2–4 Hz as well. This frequency range is commonly denoted as the delta-band, but was also identified as lower theta-band in some studies, indicating that the old-new effect might be reflected in the 2–4 Hz frequency range as well (cf. Burgess & Gruzelier, 1997; Klimesch, Schimke & Schwaiger, 1994; Klimesch et al., 2000). Hence, the 2–4 Hz response was included in the analyses as well. Electrodes around *Fz* covering for the frontal midline region were chosen. Based upon prior literature, an early latency range from 250 to 650 ms for the 2–4 Hz response (see Burgess & Gruzelier, 1997) and 200–600 ms for the 4–7 Hz band response were used for analyses (e.g. Guderian & Düzel, 2005; Klimesch et al., 1997b; Klimesch, Doppelmayr, Schwaiger, Winkler & Gruber, 2000; Klimesch al., 2001b; Jacobs et al., 2006). The alpha frequency band (8–13 Hz, see e.g. Berger, 1929) was analyzed at electrodes surrounding Oz, O1 and O2 in the time window from 0 to 500 ms.

Statistical analysis

Presence

The IPQ scales were determined as sum values of the respective items (in total: 14 items; general presence: one item, spatial presence: five items, involvement: four items, realness: four items). Each item could reach values from − 3 and + 3 on a 7-step likert-scale, resulting in the following minimum and maximum sumscores per scale: *General Presence* (− 3; 3), *Spatial Presence* (− 15; 15), *Involvement* (− 12; 12), *Realness* (− 12; 12).

Shapiro–Wilk-test rejected normal distribution for one of the *IPQ* scales (*General Presence*, $p < 0.05$). Therefore, the more robust Mann–Whitney *U* test as non-parametric equivalent of the unpaired *t* test was used for analysis. *Cronbach's* α was calculated for each scale, with the exception of the one-item-scale *General Presence*.

Memory performance

D′-prime (d') was calculated separately for both groups as an operationalization of memory performance. *D'* relates the hits, i.e. correct positive judgments, to the false-positive judgments ($d' = z(\text{hit}) -- z(\text{false positive})$; Haatveit et al. 2010; Swets et al., 1961; as cited in Kisker et al., 2019b) and indicates how well participants are able to distinguish between targets and distractors. *D'*-prime was calculated per group to assess the overall retrieval success (general $d' = z(\text{all hits}) - z(\text{all false positives})$).

Additionally, *d'* was separately calculated for familiarity and recollection for each group, taking only the respective hits and false positives into account (cf. Kisker et al., 2019a: d'-familiarity score = z(familiarity hits) − z(familiarity false positives); d'-recollection score = z(recollection hits) − z(recollection false positives). Shapiro–Wilk-test rejected normal distribution for all *d'* scores (all $p < 0.05$). Hence, Mann–Whitney *U* Test was used for analysis.

Accuracy [(hits + correct rejection)/total number of trials] and error rate [(misses + false positives)/total number of trials] of recognition judgements were calculated per group. Both were analyzed using the unpaired *t* test.

Prior VR experience and cybersickness

Prior experience with VR and cybersickness were assessed as nominal variables (prior experience: "*Have you already had any experience with virtual reality, e.g. studies, games or videos*?", [yes/no]; cybersickness: "*Did you experience physical symptoms such as nausea or dizziness during the experiment?*", [yes/no]; if yes: "*How strongly did you feel nauseous/dizzy*?" [1–10]; cf. Kisker et al., 2019a). Contingency tables and Pearson's Chi square (X^2) test were used for statistical analysis.

Ratings of the videos

The ratings regarding valence, arousal and motivation of the videos were collected for the validation of a database and will not be further analyzed in this study. To check that the target videos were perceived comparably emotive in both groups, arousal and valence averaged over all 50 target videos were compared between the groups using unpaired *t* test.

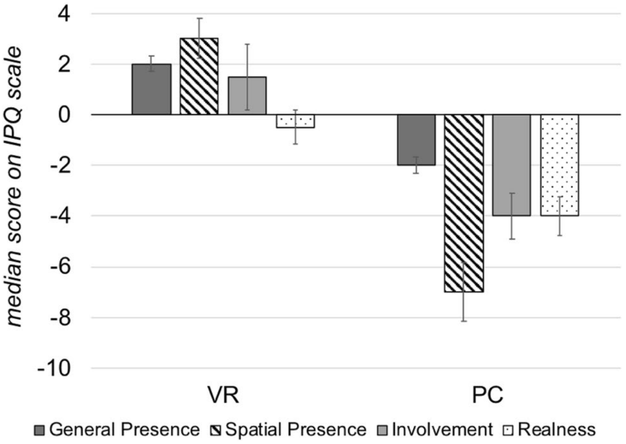


Fig. 3 Median scores of the IPQ scales General Presence, Spatial Presence, Involvement and Realness as evaluated by both groups. The error bars depict the standard error per scale. Minimum and maximum sumscores per scale: General Presence (– 3; 3), Spatial Presence(– 15; 15), Involvement (– 12; 12), Realness (– 12; 12)

Dependent measures

EEG data were analyzed using a 2 × 2 *repeated-measurements ANOVA* (rmANOVA) with the between-factor "group" (VR vs. PC) and the within-factor "condition" (new pictures vs. old pictures). Significant effects of *rmANOVA* were complemented by post hoc *t* tests.

Results

Subjective measures

Presence

As hypothesized, the VR-group reported a higher feeling of presence during video presentation (see Fig. 3). This is valid for all *IPQ* subscales (all $p \leq 0.005$; see Table 1). Cronbach's α indicates acceptable reliability for all scales (all $\alpha \geq 0.64$).

Prior VR experience and cybersickness

In both groups, about 70% of the participants had already gained experience with VR prior to the study, e.g. by participating in other studies, watching VR videos or playing VR-games ($X^2(1)=0.011$, $p=0.915$). In total, nine subjects (n_{VR}: six, n_{PC}: three) reported experiencing physical symptoms like nausea and dizziness, but on a very mild level (nausea, in total: $M=2.55$, $\mathrm{SD}=2.13$; VR: $M_{\mathrm{VR}}=3.33$, $\mathrm{SD}_{\mathrm{VR}}=2.25$; PC: $M_{\mathrm{PC}}=1.0$, $\mathrm{SD}_{\mathrm{PC}}=0.0$; dizziness, in total: $M=1.67$, $\mathrm{SD}=1.12$; VR: $M_{\mathrm{VR}}=2.00$, $\mathrm{SD}_{\mathrm{VR}}=1.27$; PC: $M_{\mathrm{PC}}=1.0$, $\mathrm{SD}_{\mathrm{PC}}=0.0$), resulting in significantly stronger experiences of physical symptoms in the VR condition ($X^2(1)=4.91$, $p=0.027$).

Ratings of the videos

Participants of both groups reported equal levels of valence and arousal averaged across all target videos (valence: $M_{\mathrm{VR}}=3.89$, $\mathrm{SD}_{\mathrm{VR}}=0.52$, $M_{\mathrm{PC}}=3.61$, $\mathrm{SD}_{\mathrm{PC}}=0.47$,

Table 1 Differences between VR- and PC-group regarding the sensation of presence, assessed via the IPQ (Schubert et al., 2001): Test statistics of the one-tailed Mann–Whitney *U* test, descriptive values and Cronbach's α per scale. Cronbach's α could not be calculated for the one-item-scale General Presence

IPQ scale	*U*	*z*	*p*	Md_{VR}	Md_{PC}	Cronbach's α
General presence	41.00	– 4.29	< .001	2.00	– 2.00	
Spatial PRESENCE	19.00	– 4.72	< .001	3.00	– 7.00	0.68
Involvement	98.00	– 2.59	0.005	1.50	– 4.00	0.70
Realness	64.50	– 3.55	< .001	-0.50	– 4.00	0.64

$t(34) = 1.67$, $p = 0.103$; arousal: $M_{\mathrm{VR}} = 2.64$, $\mathrm{SD}_{\mathrm{VR}} = 0.55$, $M_{\mathrm{PC}} = 2.65$, $\mathrm{SD}_{\mathrm{PC}} = 0.47$, $t(34) = -0.28$, $p = 0.978$).

Memory performance

Participants of both groups performed equally well on the unannounced recognition memory test, as none of the calculated d' scores revealed significant differences (d'-general: $U = 186.00$, $z = -0.11$, $p = 0.462$; d'-familiarity: $U = 150.50$, $z = -1.11$, $p = 0.14$; d'-recollection: $U = 162.50$, $z = -0.77$, $p = 0.22$; see Fig. 4).

Moreover, both groups achieved surprisingly high levels of accuracy around 90% ($t(37) = -0.505$, $p = 0.308$, $M_{\mathrm{VR}} = 0.91$, $M_{\mathrm{PC}} = 0.92$) and correspondingly low error rates ($t(37) = -0.505$, $p = 0.31$, $M_{\mathrm{VR}} = 0.09$, $M_{\mathrm{PC}} = 0.08$; see Fig. 4), indicating a ceiling effect.

Dependent measures

Since the behavioral data indicate no difference in memory performance between both groups, and since the high accuracy indicates a ceiling effect, the latency range following stimulus onset was analyzed instead of the latency range following the participants' response (key pressure) to the stimulus (cf. results, memory performance).

The visual inspection of the FFT validated the hypothesis-driven selection of the 4–7 Hz and 8–13 Hz frequency ranges. In addition, the visual inspection also revealed a noticeable power of the 2–4 Hz frequency range, which is

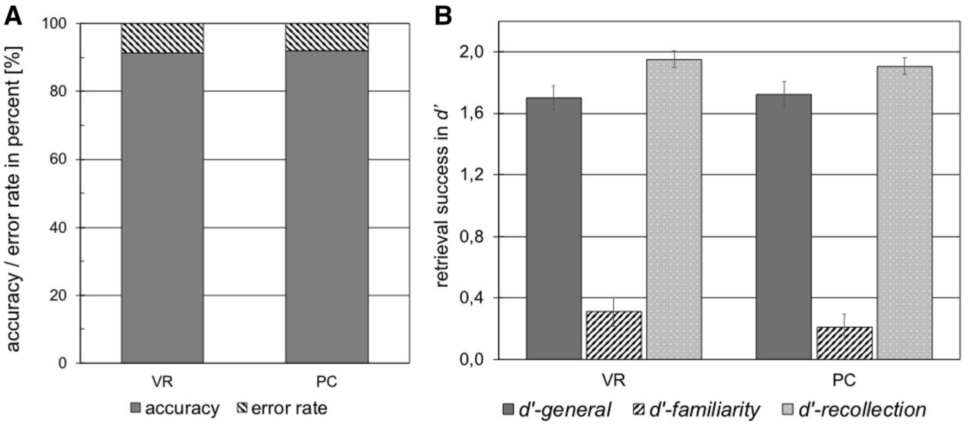
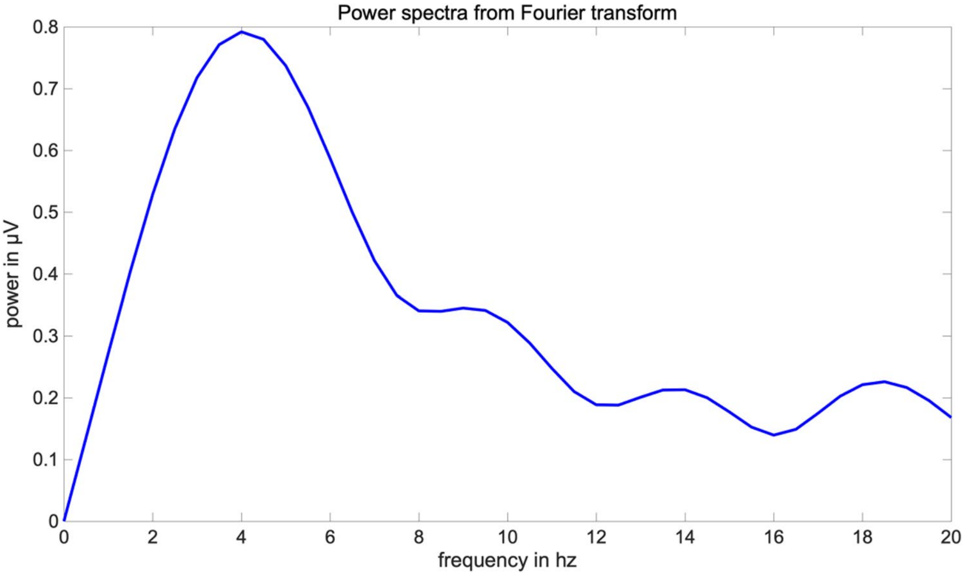


Fig. 4 Panel A depicts the accuracy as well as the respective error rate of the judgement on the recognition or unknown character of the memory task trials in percent for both groups. The error bars depict the standard errors. For accuracy and error rate, the standard error is approximately 0.01 and therefore hardly visible in the figure. Panel B depicts the retrieval success per group operationalized by general d' prime, as well as the d'-familiarity and d'-recollection scores. No significant differences were found between both groups

Fig. 5 Power spectra from fast Fourier transform (FFT) per group and condition. Visual inspection revealed a strong frequency peak from 2 to 4 Hz, which was hence included in the analyses



why it was also included in the analyses (see Fig. 5, see methods).

4–7 Hz responses

Regarding frontal-midline theta-band responses, no significant main effects could be found ($F_{\text{condition}}(1{,}37) = 2.84$, $p = 0.10$; $F_{\text{group}}(1{,}37) = 0.38$, $p = 0.543$), but a significant interaction of the factors “group” and “condition” ($F_{\text{interaction}}(1{,}37) = 5.03$, $p = 0.046$).

Post-hoc *t* tests revealed a classical old/new effect in the PC condition with a higher amplitude for old pictures than for new ones ($t(18) = -2.86$, $p = 0.010$). However, this difference effect was absent within the VR condition ($t(19) = 0.25$, $p = 0.805$). Furthermore, the observed difference effect was comparably larger in the PC-group ($t(37) = 2.06$, $p = 0.046$; see Figs. 6 and 7). The theta-band response to new pictures ($t(37) = -0.14$, $p = 0.889$) and to old pictures ($t(37) = 1.65$, $p = 0.107$) did not differ between both groups (see Figs. 6, 7 and 8).

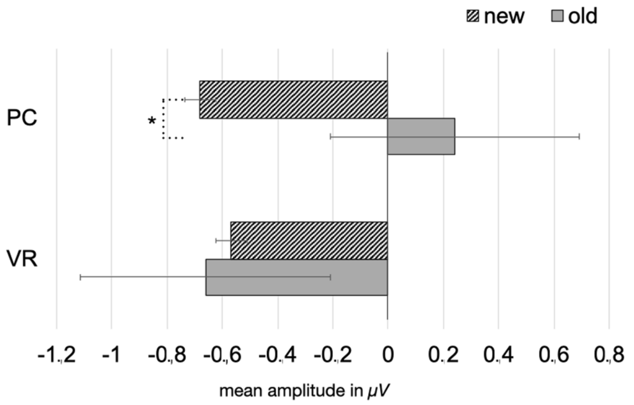


Fig. 6 Mean amplitude in μV regarding the 4–7 Hz response in the latency range from 200 to 600 ms after stimulus onset. The error bars depict the standard error of the mean amplitude. Significant differences are marked (*$p < 0.05$)

2–4 Hz responses

For the 2–4 Hz response, a significant main effect for the factor “condition” ($F_{\text{condition}}(1{,}37) = 11.61$, $p = 0.002$), but not for the factor “group” ($F_{\text{group}}(1{,}37) = 1.44$, $p = 0.239$) could be found. The main effect of “condition” was further characterized by a significant interaction of both factors ($F_{\text{interaction}}(1{,}37) = 4.11$, $p = 0.049$). Following the same trend as the 4-7 Hz responses, post hoc *t* tests revealed a classical old/new effect across conditions ($t(38) = 3.23$, $p = 0.003$), as well as in the PC condition ($t(18) = -4.74$, $p < 0.001$), but not in the VR condition ($t(19) = -0.85$ $p = 0.404$). Again, the observed difference effect was comparably larger in the PC-group ($t(37) = 2.03$, $p = 0.049$). But most importantly, old pictures elicited greater responses in the PC group compared to the VR-group ($t(37) = 2.07$, $p = 0.046$), whereas responses to new pictures did not differ between both groups ($t(37) = -0.05$, $p = 0.96$; see Figs. 9, 10 and 11).

Alpha-band responses

Regarding the alpha-band responses (8–13 Hz) at occipital electrodes, a main effect of the factors group ($F_{\text{group}}(1{,}37) = 4.26$, $p = 0.046$) and condition ($F_{\text{condition}}(1{,}37) = 13.80$, $p < 0.001$), but no significant interaction of both factors was found ($F_{\text{interaction}}(1{,}37) = 1.21$, $p = 0.278$).

Fig. 7 Time-by-amplitude plot of the 4–7 Hz response from 200 ms before stimulus onset to 1200 ms after stimulus onset. While the classical old/new-effect is also descriptively shown in the PC condition, there are no significant differences between old and new pictures regarding the VR-group. The gray highlighted section marks the latency range of significant interaction. The amplitude was averaged across the electrodes around Fz, covering for the frontal midline region

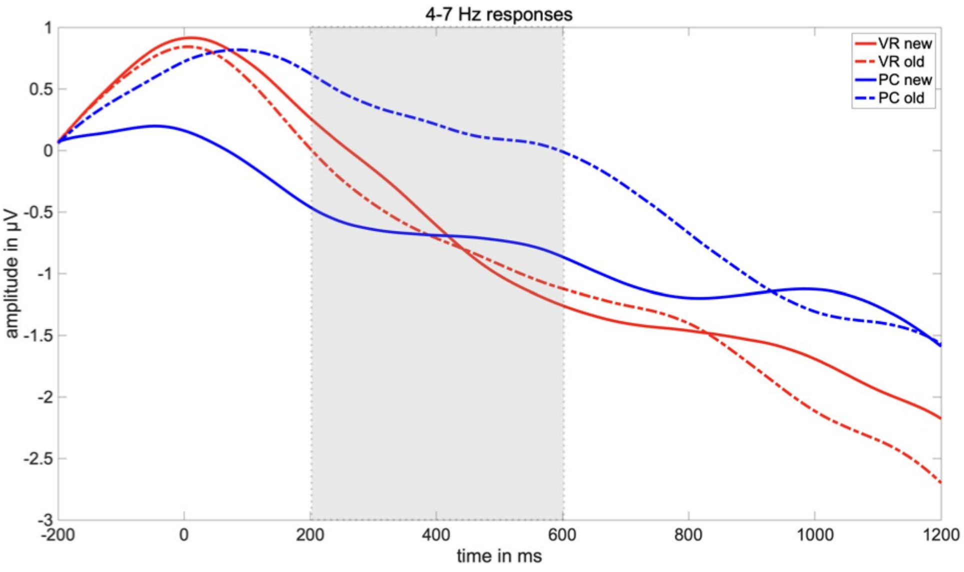
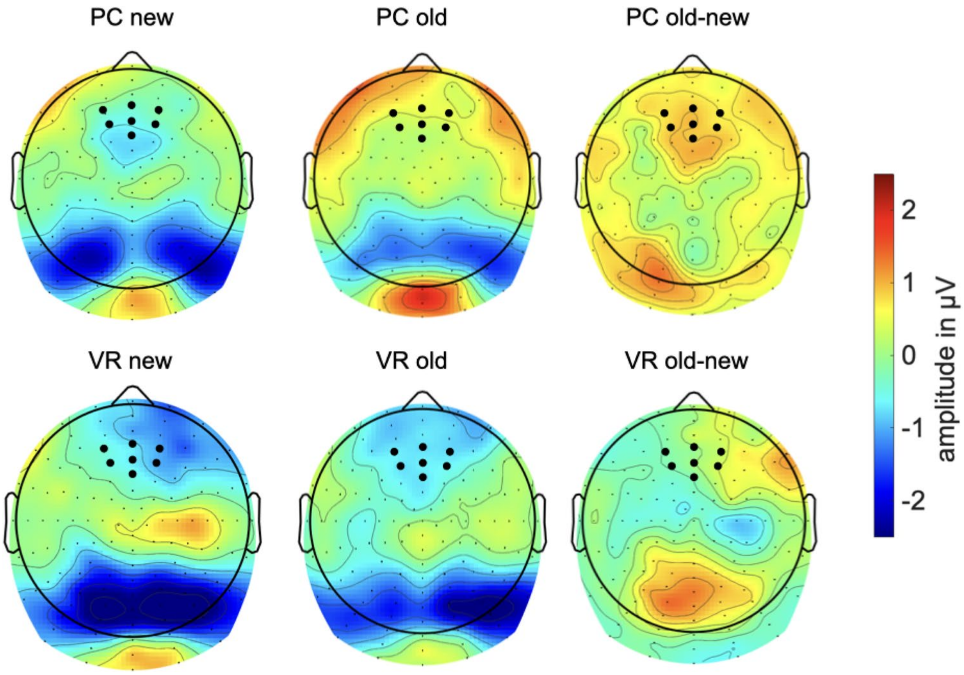


Fig. 8 Topography of the amplitude regarding the 4–7 Hz response separately for all combinations of the factors group (VR vs. PC) and conditions (old vs. new) in the latency range from 200 to 600 ms after stimulus onset. Additionally, a difference plot of the old/new-effect is depicted. Black dots mark the electrodes which were included in the analyses



More specifically, new pictures elicited lower alpha amplitudes as compared to old pictures ($t(38) = 3.68$, $p < 0.001$). In line, alpha amplitudes were significantly lower for the PC group as compared to the VR group ($t(76) = 2.75$, $p = 0.008$; see Figs. 12, 13 and 14).

Discussion

The aim of the study was to investigate the electrophysiological correlates of the retrieval of VR experiences as opposed to conventional laboratory experiences. To this end, participants watched either 3D-360° VR videos (VR condition) from the *luVRe* database (see methods), or watched the exact same stimulus material on a conventional 2D monitor (PC condition). In an unannounced recognition test, we compared their memory performance, the mid-frontal theta old/new effect indexing mnemonic processing, as well as posterior alpha as a marker for visual processing load. As a result, both groups performed equally well in the recognition test, although the theta old/new effect could only be replicated for the PC condition and was absent in the VR condition. Additionally, the theta effect was accompanied by a profound reduction of posterior alpha in the PC condition, indicating a visually guided, effortful retrieval process.

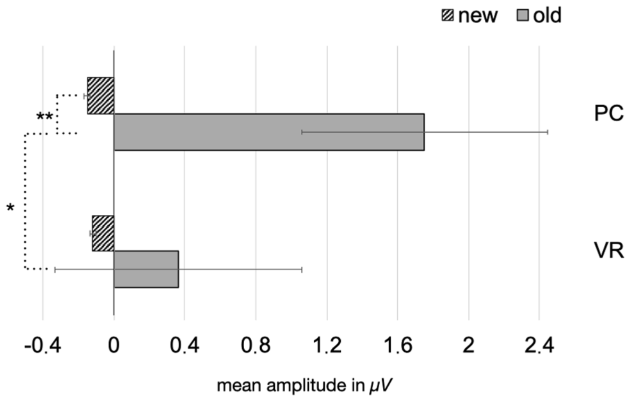


Fig. 9 Mean amplitude in µV regarding the 2–4 Hz response in the latency range from 250 to 650 ms after stimulus onset. The error bars depict the standard error of the mean amplitude. Significant differences are marked (*$p < 0.05$; ** $p < 0.01$)

Meeting our expectations, participants of the VR condition felt more present during video presentation as compared to the PC condition, confirming that our video approach led to immersive VR experiences. Presence, as the most prominent feature of VR experiences (e.g. Schubert et al., 2001, Pan & Hamilton, 2018; Diemer et al., 2015; Alshaer, Regenbrecht, & O'Hare, 2017; Riva et al., 2007; Kisker et al., 2019a), is associated with increased emotional involvement (e.g. Gorini et al., 2010; Felnhofer et al., 2015), and stronger and more realistic behavioral responses as compared to conventional laboratory settings (Slobounov et al., 2015; Kisker et al., 2019a). Importantly, previous studies found that a high degree of presence aids memory recall: For example, both intentional encoding, as well as incidental encoding in a VE resulted in a more accurate memory recall as compared to conventional desktop conditions (e.g. Krokos, Plaisant & Varshney, 2019; Ernstsen, Mallam & Nazir, 2019). Hence, presence might facilitate encoding processes constituting the VR memory superiority effect (Makowski, Sperduti,

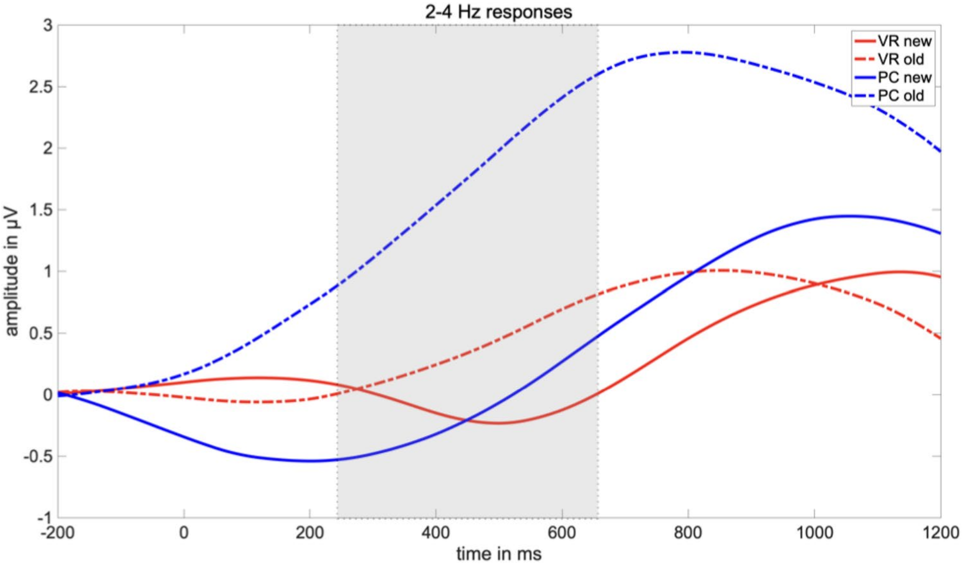


Fig. 10 Time-by-amplitude plot of the 2–4 Hz response from 200 ms before stimulus onset to 1200 ms after stimulus onset. The gray highlighted section marks the latency range of significant interaction. The amplitude was averaged across the electrodes around Fz, covering for the frontal midline region

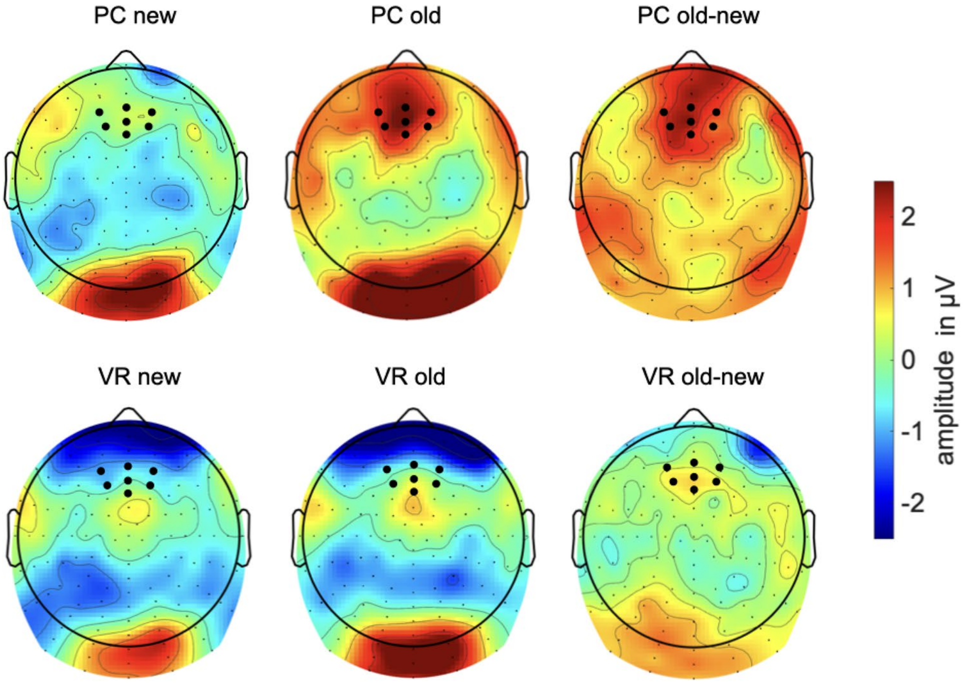


Fig. 11 Topography of the amplitude regarding the 2–4 Hz response separately for all combinations of the factors group (VR vs. PC) and conditions (old vs. new) in the latency range from 250 to 650 ms after stimulus onset. Additionally, a difference plot of the old/new-effect is depicted. Black dots mark the electrodes which were included in the analyses

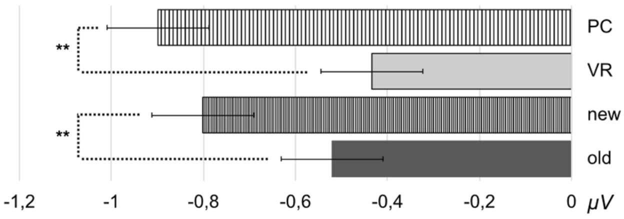


Fig. 12 Mean alpha amplitude (8-13 Hz) in µV in the latency range from 0 to 500 ms after stimulus onset. The error bars depict the standard error of the mean amplitude. Significant differences are marked (*$p < 0.05$; **$p < 0.01$)

Nicolas & Piolino, 2017; Serino & Repetto, 2018; Smith, 2019). In particular, visually detailed environments that provide high realism and resemblance to the real world, such as 3D-360° videos (Pan & Hamilton, 2018; Lovett et al., 2015), facilitate more accurate judgments in old/new tasks (Smith, 2019). The resulting coherent egocentric perspective facilitates recollection and reliving of such content (see Rubin & Umanath, 2015), which is crucial to form vivid, real-life memories (Conway, 2005; Roediger & Marsh, 2003). Hence, a high sense of presence—including sensations of spatial presence, involvement and realness—means that

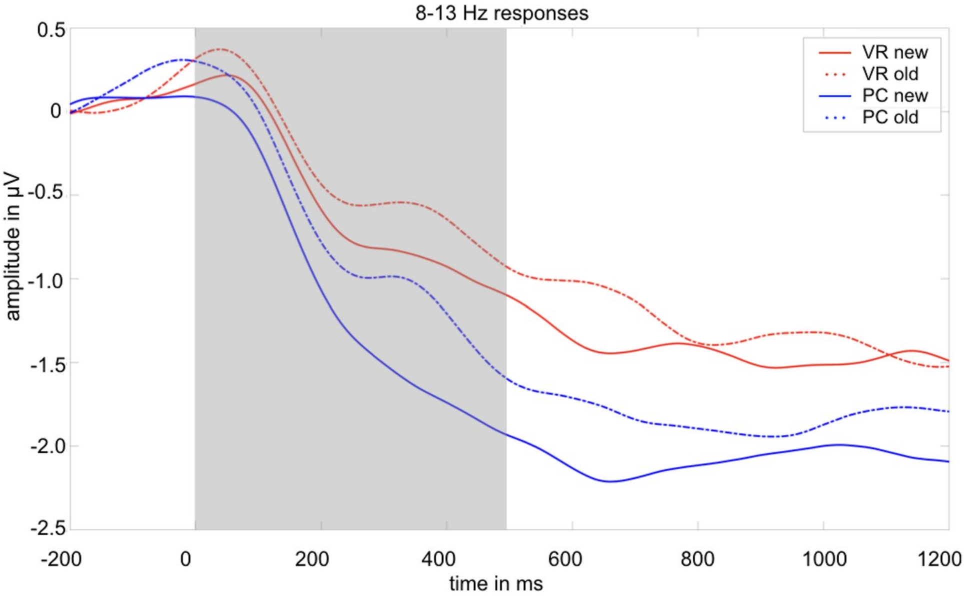


Fig. 13 Time-by-amplitude plot of the alpha-band response (8–13 Hz) from 200 ms before stimulus onset to 1200 ms after stimulus onset. Descriptively, a stronger reduction of the alpha amplitude was observed for both PC conditions compared to both VR conditions. The gray highlighted section marks the latency range of both significant main effects

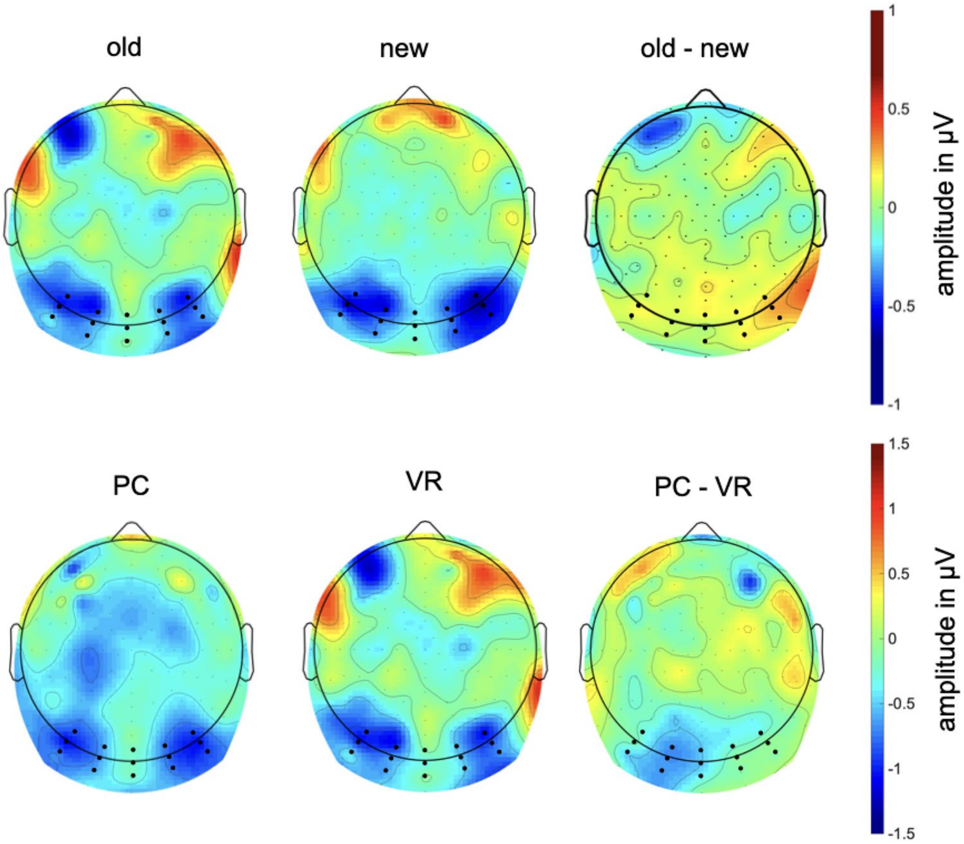


Fig. 14 Topography plot of alpha amplitude in µV (8–13 Hz) separately for factors group (VR vs. PC) and conditions (old vs. new) in the latency range from 0 to 500 ms after stimulus onset. Additionally, a difference plot of old minus new and PC minus VR is depicted. Black dots mark the electrodes which were included in the averaged amplitude

these events are potentially significant for the participant, consciously experienced and thus, might contribute to the formation of autobiographical memory.

However, at odds with previous research (Schöne et al., 2019; Smith, 2019; Kisker et al., 2019b), our study did not provide any behavioral evidence for this effect: Even though the VR group reported higher sensations of presence as compared to the PC group, we did not observe superior memory recall performance. Our results, with both groups having an accuracy of ca. 90%, indicate a ceiling effect, limiting the detection of group differences (Bortz & Döring, 2005). A possible cause of is effect might be the short retention interval between encoding and retrieval. Previous studies, which did not apply EEG measurements, chose longer retention intervals that included one or two sleeping periods (Schöne et al., 2019; Kisker et al., 2019b). It is possible that the process of forgetting irrelevant information had not yet started at the time of the EEG measurement or had at least not progressed very far (cf. Wang, Subagdja, Tan & Starzyk, 2012). However, other studies have not been able to demonstrate this overall memory superiority of VR experiences either (LaFortune & Macuga, 2018; Dehn et al., 2018; Kisker et al., 2019b). Differences regarding the findings of VR studies might be related to varying implementations of VR technology, ranging from highly immersive head-mounted displays and CAVE systems to less immersive desktop-VR implementations (Smith, 2019). Additionally, the level of multi-sensory sensations provided by the VR system might influence memory performance as well: For example, active navigation through a VR environment can have an additional positive effect on spatial memory, but not necessarily on factual memory (Plancher, Barra, Orriols & Piolino, 2013). Moreover, some studies report a successful transfer of content learned in an immersive VR environment to real-life, and thus, to other than the encoding context (Ragan, Sowndararajan, Kopek & Bowman, 2010; as cited in Smith, 2019), whereas other studies claim that knowledge transfer comes with a loss of performance (Lanen & Lamers, 2018).

Even though VR experiences do not necessarily increase the retrieval success as measured by subjective reports, the immersive nature of VR yet might alter the mode of operation of the mnemonic mechanisms. Specifically, Kisker et al., (2019a) demonstrated by means of a remember/know paradigm that participants who explored a virtual village in an immersive VR condition report predominantly recollection-based memory. Interestingly, recollection is hypothesized to be the associated retrieval mechanism of autobiographical memory (Roediger & Marsh, 2003; Conway, 2005). Participants exploring the very same village in a PC condition reported predominantly familiarity-based memories (Kisker et al., 2019a). However, both groups in our experiment apparently employed the same retrieval strategies as the d'-scores for recollection, familiarity and overall performance do not differ significantly.

Nevertheless, modulations of the frontal-midline theta effect might still indicate the involvement of different types of memory systems as well as associated encoding and retrieval strategies with respect to the encoding condition. As expected, we replicated the frontal-midline theta old/new effect in the PC condition: Old pictures evoked an early theta-band synchronization, whereas new pictures resulted in theta-band desynchronization. Hence, our findings replicate broad and stable evidence relating relatively higher theta-band amplitudes to the retrieval of old, and relatively lower amplitudes to the retrieval of new pictures in conventional laboratory settings (e.g. Gruber et al., 2008; Klimesch et al., 1997a, b, 2001a, b). The change of modality, i.e. encoding videos, but retrieval in response to picture presentation, did not markedly affect the theta old/new effect in the PC condition.

Remarkably, the theta old/new could not be observed in the VR condition. Specifically, new pictures led to the same theta-band response in both groups, indicating that the physical discrepancies between encoding in VR or under conventional conditions did not affect the paradigm per se or at least affected it to the same extent. Moreover, memory success did not account for the different electrophysiological responses as well, as both groups performed equally well in the recognition test. Accordingly, differences in the electrophysiological response must result from different underlying retrieval mechanisms and thus, differences in mnemonic processing of engrams encoded from either VR experiences or conventional laboratory events. Evidence that the absence of the theta old/new effect under VR conditions results from an altered mnemonic processing style as compared to the PC condition is obtained from the comparison of the response to old pictures between both groups. Regarding the 2–4 Hz frequency range, the presentation of old pictures led to a significant difference between relative synchronization in the PC group and in the VR group. Descriptively, the 4–7 Hz frequency range follows the same trend but did not reach significance. Hence, the theta old/new effect is modulated by the nature of the engram resulting from VR experiences and how these experiences are recalled.

As aforementioned, immersive VR experiences are considered to facilitate the formation of autobiographical memory. Associative autobiographical engrams are generated by highly self-relevant experiences (Roediger & Marsh, 2003; Conway, 2005). They are characterized by richer content and are deeply interwoven into existing memory structures (McDermott et al., 2009; Roediger & Marsh, 2003). Furthermore, they come with a broad set of functional properties, namely self-reflection, emotional evaluation and semantic processes (Svoboda et al. 2006). Frontal-midline theta has repeatedly been shown to reflect key-elements of autobiographical mnemonic processing. Specifically, it is associated with the recollection of personal events and contextual information (Guderian & Düzel, 2005; Hsieh & Ranganath, 2014; see also Roediger & Marsh, 2003; Conway, 2005). In line with previous studies, our results indicate that the retrieval of immersive 3D-360° experiences differs from the retrieval of conventional 2D laboratory events (Schöne et al. 2016; Schöne et al. 2019; Kisker et al., 2019b). Hence, the well-established theta old/new effect does not seem to be unrestrictedly applicable to VR experiences. It might rather serve as an index for cue-matching of previously exogenously processed pictorial stimuli: Experiences encoded in the laboratory are recalled and visually matched to the test stimuli, but are not inevitably associated with the vivid and multimodal character of autobiographical memories and thus, might not provide a holistic representation of real-life mnemonic processing.

The question remains, which processes change their mode of operation in response to the recall of VR experiences. The theta old/new effect is predominantly associated with retrieval success (e.g. Nyhus & Curran, 2010). However, the VR and the PC group were likewise successful in the recognition task. As above mentioned, frontal-midline theta is associated with autobiographical mnemonic processing, but also regarded as an index for top-down control of memory retrieval (Klimesch et al., 1997b; Nyhus & Curran, 2010). Specifically, early theta-band increases indicate an attempt or the effort demands to retrieve engrams rather than successful retrieval per se (Klimesch et al., 2001a; Nyhus & Curran, 2010). Several studies investigating memory retrieval in general as well as the classical old/new effect in particular, explicitly differentiate retrieval effort and retrieval success (Klimesch et al., 2001a; Nyhus & Curran, 2010; Rugg et al., 1998; Konishi, Wheeler, Donaldson & Buckner, 2000). In particular, processes exclusively associated with retrieval success are engaged only if an attempted retrieval is successful. In contrast, retrieval effort refers to those processes engaged during a retrieval attempt per se, for example in recognition tasks, regardless of whether this attempt is successful or not (Rugg, Fletcher, Frith, Frackowiak & Dolan, 1996). Accordingly, the absence of a difference in memory success does not rule out that the effort required to achieve the very same retrieval outcome may vary.

Hence, the difference in the theta-band response to old pictures between the VR condition and the PC condition could reflect the two types of retrieval differing with respect to their effort demands (Conway, 1996; Haque & Conway, 2001; Conway & Pleydell-Pearce, 2000). Immersive VR experiences as part of an extensive autobiographical associative network (PBM, Schöne et al., 2019) can be effortless and, most of all, directly retrieved. In contrast, the retrieval of conventional stimuli triggers the iterative verification process and the suppression of irrelevant information, thus coming in with higher effort to recall memories. Direct retrieval of autobiographical memory is based upon a pronounced and stable memory pattern (Conway & Pleydell-Pearce, 2000) and enables spontaneous recall, which is rather automatic and effortless (Conway & Pleydell-Pearce, 2000 as cited in Willander & Larsson, 2007). It thus allows immediate recall of a cued memory. Generative or strategic retrieval of conventional stimuli, as observed in the PC condition, relies on central control of memory recall (Willander & Larsson, 2007). To verify the cued memory, irrelevant information has to be suppressed, while mental representation and cue are matched (Norman & Bobrow, 1979; Conway, 1996; Burgess & Shallice, 1996).

This interpretation of a visually guided matching process gains further support from the difference in posterior alpha oscillations, associated with visual processing (e.g. Clayton et al., 2018). Matching mental representation and cue is reflected by a generally reduced posterior alpha amplitude in the PC condition compared to the VR condition. This reduced alpha amplitude, commonly regarded as cortical activity (e.g. Berger, 1929 as cited in Klimesch et al., 1997b), on the one hand reflects elevated attention (e.g. Klimesch, et al. 1997a; Fries, Womelsdorf, Oostenveld & Desimone, 2008) and, on the other hand, successful suppression of irrelevant information (Sauseng et al., 2009; Jensen & Mazaheri, 2010). Especially, the co-occurrence of higher frontal theta responses and posterior alpha activity has been interpreted as a response to higher cognitive load, with 2D environments exhibiting higher cognitive load as compared to 3D environments (Dan & Reiner, 2017). Theta and alpha oscillations thus provide evidence for effortless and direct retrieval of immersive VR experience and a, in comparison, effortful and strategic retrieval of conventionally presented stimuli.

Nevertheless, the finding that the retrieval mechanisms underlying VR experiences and conventional laboratory experiences differ, does not invalidate previous well-established knowledge gained from conventional setups. Rather, it complements the immense insights from previous studies and demonstrates the delicate balance between high experimental control and ecological validity. Thus, controlled laboratory studies provide the foundations for understanding the complex mechanisms of human memory and are substantial for developing models. As a further refinement of these foundations, VR settings facilitate the transfer of experimental findings to everyday life and thus improve their generalizability and practicability.

Conclusions

As a conclusion, we replicated the well-established theta old/new effect in a conventional laboratory setting, manifested in relative theta-band synchronization for old, and relative desynchronization for new stimuli. However, this effect could not be replicated for the immersive VR condition: Theta-band responses were equal for old and new stimuli. Hence, the canonical theta old/new effect might not be unrestrictedly applicable to VR experiences and thus, might not provide a holistic representation of real-life processes. Accompanied by higher alpha activity as compared to the VR condition, the theta-band synchronization in the PC condition might rather reflect higher retrieval effort than retrieval success per se. In contrast to laboratory events, memories obtained from VR experiences are spontaneous and effortless retrieved. Additionally, participants of the VR condition reported a higher sense of presence, which might enhance the self-relevance of the VR experiences. Crucially, self-referential processing and a facile, effortless recall are characteristic of autobiographical memory. Therefore, the effortless recall of VR experiences might approximate real-life memory more closely as compared to memories obtained from the laboratory. However, the VR group did not perform better in the memory test, as former research suggested. Hence, our results suggest that the memory processes underlying VR experiences are qualitatively different from conventional laboratory experiences, but under which conditions VR leads not only to altered mechanisms but also to a better memory performance compared to conventional settings should be the subject of further research.

Author contributions All authors contributed to the study design. Testing and data collection were performed by JK. Data analyses were performed by JK under the supervision of BS and TG. JK and BS performed the data interpretation under the supervision of TG. JK drafted the manuscript, and BS and TG provided critical revisions. All authors approved the final version of the manuscript for submission.

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Availability of data, material and code The datasets generated and analyzed during the current study are available in the Open Science Framework (OSF) repository, https://osf.io/q924w/?view_only=cc107f7a927f472e8e68e85aaa059e97. Stimulus material was obtained from the Library for Universal Virtual Reality Experiments (luVRe, https://www.psycho.uni-osnabrueck.de/fachgebiete/allgemeine_psychologie_i/luvre.html) and can be accessed upon request.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Statement of ethical approval All procedures performed in this study involving human participants were in accordance with the ethical standards of the local ethic committee of Osnabrueck University and with the 1964 Helsinki Declaration.

Consent to participate and to publish All individual participants gave informed written consent to participate in the study and to anonymized publication of the datasets.

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3. General discussion

3.1 Summarized results

The empirical studies aimed to investigate whether and which cognitive-affective research findings change and which remain unchanged when the ecological validity of research methods is increased by employing virtual reality (VR) paradigms. To this end, a standard emotion elicitation paradigm, an approach-avoidance task and two memory retrieval tasks were translated to VR settings (see Table 1., p. 20). The *motivation study* (Study 1.1) investigated whether emotional-motivational mechanisms deployed in VR correspond to those under conventional laboratory settings by means of the electrophysiological correlates of approach/avoidance tendencies. The frontal alpha asymmetry (FAA) as the ratio between left and right frontal alpha-band power is indicative of frontal cortical activity and has been broadly associated with approach-avoidance motivation (e.g., Harmon-Jones & Gable, 2018; Hewig, 2018). The electrophysiological response to the same stimulus material presented in either an immersive 3D-360° condition or a 2D condition was evaluated. Not only did the FAAs differ in intensity concerning each of the videos, but the responses to the 3D-360° and 2D conditions were opposed concerning 14 of 15 videos, indicating fundamentally different processing styles depending on the presentation mode. Existing models could only be applied speculatively to the FAA data obtained from the VR condition but in particular could not cover the contrasting responses observed across both conditions. Consequently, well-known FAA models did not translate to VR conditions without loss. Yet they give rise to the assumption that the emotional-motivational tendencies as indicated by the FAA under VR conditions reflect more natural responses compared to the 2D condition.

The latter was further investigated by the *cave study* (Study 2), which was extended to include full-body behavioral responses to an immersive environment. Beyond previous findings, a frightful cave not only yielded intense negative affect but also elicited realistic behavioral expressions of fear. While the neutral group casually explored the cave, participants in the negative condition either quickly advanced toward a werewolf to get past it, or hesitated or even hid when encountering it. These strongly expressive behaviors could only be partially discriminated based on the FAAs and could not be interpreted according to the existing models. Moreover, for the greater part of the cave exploration, no differences were found between the electrophysiological responses of the neutral and the negative groups. Therefore, the implications of the study are twofold: On the one hand, our results show that VR does not only trigger the affective component of the fear response but also natural full-body reactions. Behavioral responses were captured more directly, since the participants did not need to translate them into a substitute action. Thus, the incremental value of the *cave study* (Study 2) is to allow for natural behavioral responses rather than keystrokes and to obtain these in combination with the corresponding electrophysiological data, i.e., FAAs. On the other hand, our results imply that models derived based on conventional laboratory settings, e.g., models on the role of FFAs, are not straightforwardly generalizable to real-world processes, although the electrophysiological responses partly differentiated between groups.

Complementing these findings on affective processing, the *free recall study* (Study 1.2) and the *theta old/new study* (Study 3) focused on memories encoded from VR versus conventional laboratory conditions. The *free recall study* (Study 1.2) aimed to replicate the superiority effect concerning retrieval of VR experiences compared to laboratory experiences. In order to examine the generalizability of this effect, it made use of multifaceted VR footage depicting real-world environments and events instead of isolated objects to be retrieved. In the free recall of these experiences, the VR group was significantly superior to a 2D screen condition, whereas no difference was found in the subsequent cued recall of scenic details.

Further disentangling the mechanisms underlying the retrieval of VR-based engrams, the *theta old/new study* (Study 3) implemented a canonical old/new recognition task. After encoding the same stimulus material either under VR or conventional PC conditions, participants exhibited different electrophysiological patterns. Despite different electrophysiological responses, the groups performed equally well in the recognition test, which suggests that not retrieval performance but the underlying mechanisms or systems differed. The PC condition exhibited a canonical theta old/new effect, i.e., a higher theta-band response to old stimuli than to new ones during recall accompanied by significant decreases of the posterior alpha-band response. In contrast, the theta old/new effect was absent in the VR condition. Even more, the VR condition exhibited lower alpha amplitudes, indicative of a less effortful retrieval compared to the PC condition. In concert, these results suggest an effortless, immediate retrieval of VR-based engrams compared to more effortful, visually guided retrieval of conventional laboratory memories.

3.2 Aim of the general discussion

The research outcomes of the studies at hand were discussed in detail in their specific research context of the respective publication. Going one step further, the general discussion will reconcile the results and integrate them into the broader research background. Special attention will be paid to the differences between expected standard findings and those resulting from the use of VR as a methodological tool. To this end, the intersections between the studies at hand will be considered in detail (Figure 4). They serve to illustrate the junctions at which the increase of ecological validity by means of VR paradigms seems to cause differences in cognitive-affective research methods and findings based upon the studies' results and compared to standard findings. Furthermore, possible research gaps and potential upcoming studies will be outlined in their respective context.

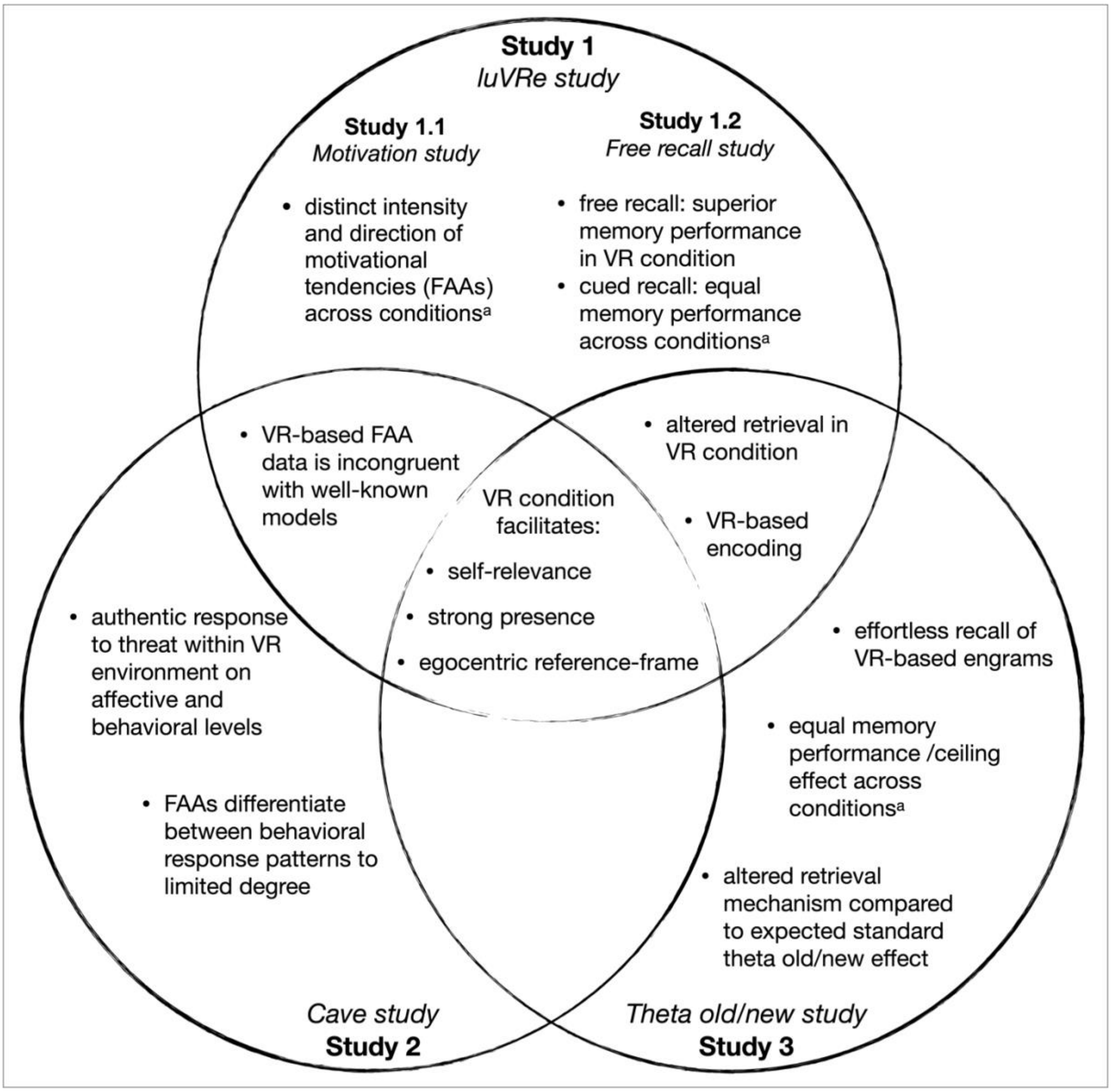
Both the *motivation study* (Study 1.1) and the *cave study* (Study 2) assessed the electrophysiological correlates of the approach-avoidance dimension by means of FAAs. In both cases, the obtained data were not or only speculatively applicable to conventional models on the role of FAAs. Accordingly, further factors beyond motivation will be addressed that may have contributed to the distinct electrophysiological responses. Moreover, the *free recall study* (Study 1.2) and the *theta old/new study* (Study 3) indicate that VR experiences are retrieved in a different way than PC-based experiences. However, both studies differ in findings on memory performance and the underlying mechanisms.

All studies overlap regarding the sense of presence, self-relevance, and an egocentric reference-frame, which are increased in VR experiences compared to conventional settings. These characteristics can be summarized and integrated in the concepts of embodied simulations and a shared 3D default space of VR and real-world experiences. Of course, not all changes in the research findings by means of the differences between VR and conventional paradigms can be conclusively explained on the basis of the four studies at hand. Rather, the studies provide initial explanatory approaches which are examined without claiming conclusive exhaustiveness. For better readability, the studies at hand are referred to hereinafter with their respective labels instead of numbering in the body text (see Figure 4;

Study 1.1: *motivation study*; Study 1.2: *free recall study*; Study 2: *cave study*; Study 3: *theta old/new study*).

Figure 4.

Venn diagram as a summary and overview of the studies' main results.



Note. The focus of the general discussion lies particularly on the intersections between Study 1.1 and Study 2, Study 1.2 and Study 3, and the differences common to all studies when compared to conventional experimental settings. [a]Studies 1.1, 1.2 and 3 applied a VR condition and a conventional 2D condition.

3.3 Differences in affective processing

Both the *motivation study* and the *cave study* were dedicated to the investigation of affective processing of VR experiences by means of the approach/avoidance dimension. The *motivation study* aimed to disentangle whether emotional mechanisms deployed in VR correspond to those under conventional laboratory conditions by means of FAAs. Going one step further, the *cave study* additionally examined the behavioral component, putting to the test whether the well-established electrophysiological markers would correspond to realistic behavioral responses as well. Both studies provide evidence that electrophysiological correlates obtained from conventional laboratory setups by means of FAAs do not translate to VR conditions without loss. They amplify doubts about whether the response to conventional stimuli can be transferred to other forms of presentation, including real-world experiences.

For the *motivation study*, only the presentation mode was varied between groups: The video presentation either in immersive 3D-360° VR or on a large virtual 2D screen resulted in significantly different FAA responses. Not only did the intensity of the asymmetries vary between groups but also their respective direction. With respect to well-known FAA models, VR experiences consequently do not only result in a more intense experience, as the positive correlation between emotions and presence implies (see e.g., Gorini et al., 2010), but also alter its quality. While differences between 2D and 3D were evident across all videos in the *motivation study*, the negative and neutral caves could only be distinguished in rare exceptions based on the obtained FAAs and considering the behavioral patterns in the *cave study*. Concerning the *cave study*, is particularly noteworthy that although FAAs discriminated between the negative and neutral cave, they did so to a much lesser extent than expected and inconsistently with previous models. Particularly the absence of effects in the *cave study* was surprising, as participants showed strong emotional responses in subjective and behavioral measures. Both studies' outcomes could at best be explained speculatively by the well-known FAA models (for details see 1.4.1, Figure 2, p. 24; Study 1.1 and Study 2) and suggest that either the link between FAAs and the approach-avoidance dimension does not translate to VR paradigms or that additional factors modulate the FAA response under immersive conditions. Accordingly, considering the data exclusively in terms of the approach/avoidance dimension does not provide a sufficient explanation for the observed differences or absent effects.

As both studies assessed the FAA response during the VR simulation, their results might potentially be altered by the differences in visual features and may provide insights into the perception of conventional laboratory and 3D-360° environments. Visual features might in particular alter the electrophysiological response to immersive stimuli. Using a similar approach as the *motivation study*, Xu and Sui (2021) reported distinct brain responses to the presentation of the very same video footage presented in either a 3D-VR condition or a 2D condition. They attributed increased theta-band power in response to 3D-VR to sustained attention, decreased alpha-band power to increased visual attention and perception, and increased beta-band power to increases in visual information processing (Xu & Sui, 2021). In a similar vein, several studies found increased attentional demands in response to 3D compared to 2D stimuli (Malik et al., 2015; Ray & Cole, 1985), which might confound the emotional processing of the viewed stimuli (Ray & Cole, 1985) and results in a modified meaning of the observed FAAs. However, visual attentional processes are usually measured via sensors over occipital areas (e.g., Klimesch et al., 1997). Although the EEG sensors' positions do not correspond directly to the signal's source, it seems unlikely that the FAAs at hand correspond to the alpha-band power measured at occipital sensors linked to attentional processes.

Yet FAAs have been found to be modulated by perceptual characteristics of the stimulus material: Watching low-quality videos (less immersive) is associated with higher right frontal activity and indicates that watching high-quality videos (higher immersion) might be linked to relatively higher left frontal activity (Kroupi et al., 2014). Hence, modulations of the FAA principally go beyond the approach-avoidance dimension. The mode of presentation was varied in the *motivation study*, yet the overall quality and content of the videos was identical across groups. Moreover, the *cave study's* conditions were generally equal in visual fidelity (3D/360°, 3k resolution, 110° field of view). Particularly regarding the *motivation study*, the modifications in FAAs thus would have been expected to be similar across conditions if the observed differences were solely related to an altered perception of 3D *versus* 2D footage, e.g., consistently indicating higher left frontal activity corresponding to higher quality.

The presentation in 3D-360° is accompanied by two further changes relevant to the situations' perception: A complex environment and an egocentric perspective. The complexity of the situation is to be understood as a counterpart to sterile laboratory settings (see e.g., Parsons, 2015): Both the videos in the *motivation study* and the cave in Study 2 provide a rich, coherent context for the visible items and the events taking place. In the *motivation study*, complexity was modulated only by means of stereoscopy; in the *cave study*, it was kept generally high by keeping the caves' immersion and the overall design equal across both conditions. Similarly, Rodrigues and colleagues (2018) demonstrated that FAA data from their desktop-VR study, applying a more complex environment (interactive maze) instead of isolated stimuli, were related to the motivational direction model. The finding that this link was stable under more complex conditions suggests that modifications of the FAAs cannot be attributed solely to differences in the complexity of the stimulus material. In contrast, the egocentric perspective that participants automatically occupy in VR settings might have a stronger impact on the situation's perception compared across groups.

The egocentric processing of the visual environment facilitates a self-centered spatial reference frame similar to natural perception of real-world environments from a first-person perspective (Kober et al., 2012). Conversely, in 2D conditions an allocentric reference frame or even meta-perspective is adopted, linked to an environment-centered view. The change in perspective of an event significantly impacts the electrophysiological response to observed actions. For example, action observation from an egocentric perspective corresponds to stronger reactivity of the alpha-band and beta-band oscillations as compared to allocentric viewpoints (Angelini et al., 2018). The observable actions within the videos in the *motivation study* may not only impact the opposing FAAs between groups but may also explain the disparity that FAAs within the VR group did not always change as uniformly as might have been expected if the differences in FAAs depended on, e.g., stereoscopy alone. For example, the egocentric reference frame triggers the perception of proximity (Åhs et al., 2015; Slater & Sanchez-Vives, 2016) and might vary depending on the video content, while the proximity to the stimulus does not vary in screen settings. Although the magnitude of actions was kept equal across conditions in the *cave study* (e.g., a living creature advanced toward the participant), the character of the action (harmless sheep versus attacking werewolf) might further modulate the sensorimotor response which could be reflected in the distinct alpha-band responses.

Overall, these exemplary considerations of the visual properties of the experimental situation imply that differences in the electrophysiological responses between VR and conventional settings could principally arise from altered visual processing. Even regardless of the specific functional interpretation of these findings, they indicate that electrophysiological processes and mechanisms may vary as a function of immersion irrespective of affective load (Xu & Sui, 2021).

Still the electrophysiological differences found between groups across the *motivation study* and the *cave study* cannot be attributed to the differences in visual processing alone. In contrast to the *motivation study*, the *cave study* evaluated FAA responses to equally immersive experimental conditions but varying in their affective content. Both conditions provided the same quality at the visual level and equal levels of immersiveness, e.g., with respect to stereoscopy and haptics. Although only few significant differences were found, the groups could partially be differentiated based on the respective FAAs when considering their behavioral response to the experimental situation.

Beyond mere differences in visual features, the participants perspective might alter their subjective appraisal of the experimental situation and/or stimuli. As outlined in the introduction, a crucial characteristic and benefit of VR settings is their ability to envelop the user and facilitate the sensation of presence within the virtual environment (VE; see e.g., Cipresso et al., 2018). The latter has been widely associated with intense emotions in VR experiences (Diemer et al., 2015; Felnhofer et al., 2015). Consequently, the subjective affective experiences might provide further clarification of the differences found. In the *motivation study*, we refrained from recording the participants' subjective emotional state. While conventional studies implement ratings, e.g., via visual analog scales or numerical verbal ratings (e.g., Li et al., 2017), implementing a rating of a VR experience is more difficult. Pre- and post-measurements of affect across all videos would not have provided significant insight into the emotional experience because the 15 videos were randomly presented and differed in valence. Accordingly, a separate rating would have had to be assessed after each stimulus. This would have reduced immersion after each video and potentially broken the sense of presence (see Study 1.1 for details). In contrast, the *cave study*, as a one-trial assessment, allowed for the recording of the experienced affect immediately following the experience. Participants in the negative condition reported intense negative affect, the urge to avoid the werewolf and to leave the cave as soon as possible, which was even more intense when participants exhibited retreating behavior compared to advancing behavior. In contrast, participants in the neutral condition stayed rather unaffected. Thus, in line with previous research, the respective VEs triggered emotional responses as expected on the subjective and behavioral level (e.g., Felnhofer et al., 2015; Kisker et al., 2021a; Riva et al., 2007). Especially the reported motivation to put great distance between themselves and the werewolf would have suggested that the negative cave triggers a strong avoidance motivation, albeit not reflected in the respective FAAs.

Yet one component that potentially modulates the affective appraisal of an experience has not been part of the examination in previous studies. As Kihlstrom (2021) pointed out, humans are no passive observers by nature. In most laboratory studies, however, they are treated as such when exposed to stimuli to which they cannot respond other than by pressing a button or changing their gaze direction. They rarely have a way of manipulating the situation. In stark contrast, interactive features of VR experiences allow participants to take an active role within the virtual environment (VE; Slater & Wilbur, 1997). A multidimensional (Parsons, 2015) and self-relevant (Kisker et al., 2021b; Schöne et al., 2019) experience is promoted in turn. In particular, these characteristics give reason to assume that an affective VR experience is appraised differently than an affective screen experience, which is comparatively less self-relevant and only observed instead of actively participated in (Schöne et al., 2019). The former experience thus promotes the impression that, being inside the VE, the participants can be affected by their surroundings and affect them in return (Kisker et al., 2021a; Schöne et al., 2019). The VE and occurrences therein become self-relevant, which can alter attentional effects even during early processing stages, shifting the focus to emotional stimuli relevant to the self (Fields & Kuperberg, 2012). Conversely, conventional screen experiences retain the meta-awareness that the presented situation cannot directly impact the participant, as when observing an event only through a windowpane (Schöne et al., 2019; Slater & Wilbur, 1997). Responding to a stimulus that cannot be manipulated and has no direct impact beyond sensory input might trigger fundamentally different processes than one that can be manipulated, even if both modes of presentation might lead to equivalent ratings of the stimulus's valence *per se*. Thinking back to the spider in the drawer (see 1.4, p. 16ff.), someone who has an aversion to spiders might tend to rate both, conventional screen- and VR-confrontation with a spider as negative. Among them, the egocentric VR experience is more self-relevant, since the spider may immediately impact the participant and vice versa. For example, it might on the one hand pose a threat but on the other hand, there is also an opportunity of overcoming this threat through one's own initiative. This combination of self-relevance and self-efficacy (e.g., Lin, 2017) might lead for instance to a negative situation not solely appraised as such but also facilitates coping opportunities that alter the pure experience of negative affect. Moreover, VR offers a multidimensional experience not only by the presentation of a coherent context, but also by the narrative that is conveyed in the VE (Slater & Wilbur, 1997). The more the VE draws a storyline that is coherent in itself, the more plausible the VE appears. This plausibility illusion refers to the impression that the events occurring within the VE are truly happening, including the belief that those events refer directly to the self (Slater, 2009). It promotes greater emotional engagement and, more importantly, a greater amount of information that is integrated into the appraisal of the situation (see Slater & Wilbur, 1997; Slater & Sanchez-Vives, 2016). Thus, not only the amount of perceptual information but also conceptual information and their self-relevance are increased in VR experiences compared to conventional experiences (e.g., Diemer et al., 2015), resulting in distinct appraisals of the same situation depending on the presentation mode.

Especially VR’s interactive nature facilitates self-relevance and self-efficacy (Lin et al., 2018). The latter might promote intrinsic motivation (Schunk, 1995) to cope with the experience by means of the perceived action opportunities. These changes of the experience’s appraisal go beyond the approach/avoidance dimension. Rather, the results would favor the interpretation of FAA dynamics as indicative for inhibitory top-down control on executive processes (Schöne et al., 2015) and effortful control of motivation (Lacey et al., 2020). In particular, the interactivity and active role of the participant within an egocentric reference frame favor the interpretation that such experiences do not lead to avoidance or approach motivation only. Rather the possibilities of being able to manipulate the situation in one way or another are reflected in the electrophysiological response. This perception of agency is heightened under egocentric VR conditions. In line, Adolph and colleagues (2017) pointed out that FAAs do not modulate the motor response, accounting for the dissonance of the observed behavioral patterns and respective FAAs in the *cave study*. Rather, FAAs enhance attention allocation towards subjectively significant stimuli, thereby co-determining the behavioral response but not directly reflecting behavior-dependent brain dynamics (Adolph et al., 2017).

Overall, although the electrophysiological response could also be affected by variations in visual features, especially an altered appraisal of the experience seems to account for the differences in affective processing. The *motivation study* rules out the possibility that FAAs were modulated by stimulus content *per se*, whereas the *cave study* rules out modifications solely based on visual features such as 3D-360° view. What both studies have in common, however, are on the one hand the egocentric reference frame and thus increased self-relevance of VR experiences, and on the other hand the impression of being able to actively engage in the VE and ongoing events promoted by interactivity. Although these factors do not provide a final, exhaustive explanation for the data obtained in either study, they indicate a possible node at which VR experiences separate from conventional laboratory experiences, even if the very same content is presented applying different presentation modes only (*motivation study*). The affective processing of an (VR) experience might thus be modulated beyond previous dimensions (e.g., approach/avoidance; valence/arousal) by means of self-relevance, self-efficacy, and action opportunities.

3.4 Differences in mnemonic processes and mechanisms

The *free recall study* and the *theta old/new study* were dedicated to the investigation of how (well) memories encoded under immersive VR conditions are remembered compared to memories based upon conventional laboratory settings. In particular, the *free recall study* aimed to replicate the memory superiority effect found for VR experiences for multifaceted VR footage, while the *theta old/new study* aimed to examine the electrophysiological correlates of recognition memory in response to immersive VR experiences. The studies' findings are partially contradictory: While the *free recall study* provides evidence for the memory superiority effect, the *theta old/new study* found no difference in the overall memory performance between both groups but indications of fundamentally different retrieval mechanisms. However, both studies demonstrate that the retrieval of memories encoded from VR experiences differs from retrieval of conventional laboratory events. In contrast to the studies devoted to affective processing, the memory studies do not allow direct conclusions about the encoding mechanisms, because no data was collected at this stage to prevent potential interference with the EEG data (see 1.4.2). However, because the retrieval tasks in each of the studies were held constant across groups, while only the mode of presentation during encoding was varied, the results allow indirect conclusions to be drawn about differences between groups in the encoding process.

Equivalent to the presented effects of 3D-360° presentations on affective processes, the encoding of the stimulus material might equally be modulated by the presentation mode. Further evidence that the visual properties promote differences between outcomes obtained from VR and conventional settings is provided by the retrieval of VR experiences. As discussed in the *theta old/new study*, engrams formed under VR conditions are more effortlessly recalled compared to those formed under conventional screen conditions. Since the retrieval procedure was held constant for both groups, the differences found may presumably result from the encoding source. This assumption is particularly reinforced by the observation that the electrophysiological responses to old but not to new pictures differed significantly between the groups. The VR group exhibited lower theta-band responses and higher alpha-band responses to old pictures compared to the PC group. In concert, these responses indicate a spontaneous and effortless recall of VR-based engrams (see Study 3 for details). Despite the absence of superior memory performance, the proposed effortless retrieval mechanism does not negate the possibility of such superiority. It would rather be intuitive that effortless retrieval also yields better performance, as found in the *free recall study*. As both studies encoding phases were equivalent, the 3D-360° presentation mode might yield differences to 2D presentation at three subordinate levels: The sensory information delivered, the affective appraisal and the personal relevance. These levels can be mapped onto the levels of processing model (Craik & Lockhart, 1972). In a hierarchical sequence, sensory/physical features of the information are processed. Deeper processing steps involve higher cognitive functions, e.g., processing of repetitive patterns or the semantic meaning of the information. The deeper the processing, the stronger and longer lasting the resulting memory trace (Craik & Lockhart, 1972). While differences in the presentation mode *per se* might predominantly affect initial processing steps of sensory information, affective appraisal and personal relevance deliver more complex information, promoting even deeper processing of the stimulus.

As previously discussed in terms of affective processing of VR experiences (see 3.3), the same video footage depicted in 3D-360° delivers richer sensory cues compared to 2D footage. VR provides sensory information, like depth cues, that is reduced or even lost in 2D representations. Although the brain is very well able to recalculate such cues from monoscopic input, e.g., by relative size and occlusion of objects in an image (e.g., Fischmeister & Bauer, 2006; Reading, 1983; Swain, 1997), in the real world it is used to perceive these cues without such recalculations (Dan & Reiner, 2017; Fischmeister & Bauer, 2006). Accordingly, VR delivers the footage in a more natural way, enabling the brain to skip a (potential) recalculation step in VR environments, leading to altered encoding processes - if this recalculation step is performed at all for 2D material. Due to increasing interactions with displays in our daily lives, processing such stimuli is not a novel task for the brain (Dan & Reiner, 2017). In terms of efficiency, it would not be implausible that the brain accepts 2D footage as what it is - an image only - and stores it as such without sophisticated sensory processing, i.e., recalculations of said cues being triggered. In both of the former cases, richer information would be available at an earlier stage in the encoding process, which would be integrated into a broader resulting network. Even without making assumptions about the encoding process, this difference from the conventional group fits into the previously presented findings regarding the processing of 2D versus 3D stimuli: The increases in visual processing and sustained attention when processing 3D stimuli (Xu & Sui, 2021) might contribute to a deeper processing and, consequently, a lower effort in recall than 2D stimuli respectively.

Similarly, the altered affective processing which results from the egocentric perspective the participants automatically take in 3D/360° VR experiences (see 3.3) might have a share in altered mnemonic processes and mechanisms. The finding that the emotions experienced during encoding affect how the experience is remembered seems to nowadays be a law set in stone rather than still falsifiable knowledge. This fundamental rule of the convergence of emotions and memory is apparent in many everyday phenomena, such as the negativity bias (e.g., Unkelbach et al., 2020) and flash bulb memories (e.g., Neisser, 1982) but also in extremes, like post-traumatic stress disorder (PTSD; e.g., van Marle, 2015). Generally speaking, emotional experiences are thought to be remembered better – i.e., with greater accuracy and more vividly – compared to such without affective tinge (Buchanan, 2007; LaBar & Cabeza, 2006). As previously outlined, VR experiences elicit emotions different in intensity but also alter the affective quality of experiences compared to conventional laboratory ones (see 3.3). Thus, it seems intuitive that the altered affective processing might in parts mediate the differences regarding the retrieval of VR experiences compared to laboratory experiences. Although VR was proven especially effective to induce memories tinted with negative affect, e.g., negative memories of specific VR scenarios and games (Cuperus et al., 2016; Malta et al., 2020) or even PTSD-like intrusions (Dibbets & Schulte-Ostermann, 2015), less is known to-date about their retrieval compared to either 2D experiences or neutral and positive VR experiences. First insights into this gap were provided by Zlomuzica and colleagues (2016), who put to the test whether emotional states affect the recall of spatial and temporal details of neutral VR events. Surprisingly, affective states had no significant impact on the retrieval of context information, albeit participants performed worst after the induction of an anxious state. However, the study at hand investigated the effects of emotional states induced by conventional videos prior to the VR simulation on context retrieval, not the effects of emotional VR experiences. It thus allows no conclusion on whether an effect of affect would have emerged if the VR scenario itself had been varied in emotion-inducing properties. Going one step further, Cadet and colleagues (2021) assessed the memory performance for negative, neutral and positive objects in VR environments, while the context of the object itself had no specific affective tinge (i.e., a city or an island). Participants remembered emotional stimuli better than neutral ones. Yet, no difference was found between positive and negative stimuli, indicating that rather arousal than valence contributed to superior memory performance (Cadet et al., 2021), albeit they found no consistent emotional enhancement of recall performance in a previous, very similar study (Cadet & Chainay, 2020).

The current state of research leaves much room to speculate and to examine said impact of affect on memory under VR conditions. The assumption that an altered affective processing style in terms of emotional intensity and quality would alter the retrieval of the respective experience is thus mainly based upon previous findings on the interdependency of memory and emotion (Buchanan, 2007; LaBar & Cabeza, 2006). It thus needs further examination under immersive conditions. However, given the breadth of findings on this interrelationship, it would be very surprising if the distinct affective processing of VR experiences had no effect on the respective memory trace. Although Craik and Lockhart (1972) did not specifically include affective processing as a processing level, the aforementioned differences in affective processing (see 3.3) even concerning the same stimulus content (Study 1.1) deliver more complex information to the processing of the incoming information, promoting deeper processing than visual information alone (see Craik & Lockhart, 1972).

Even deeper levels of processing might be reached if the experimental situation not only provided rich, natural sensory information and affective sensations but also bore personal relevance. The latter is facilitated under immersive VR conditions (Kisker et al., 2021b; Schöne et al., 2019). Especially the differentiation of episodic and autobiographical memories fuels the assumption that the self-relevance of the experimental situation may contribute to altered mnemonic processes. Beyond the spatial and temporal context of experienced events, AMs are foremost characterized by self-referential processing of the remembered experiences (Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway, 2005; Schöne et al., 2019) enhancing personal relevance (Roediger & Marsh, 2003; Schöne et al., 2019). Such memories arise from multimodal stimuli (Greenberg & Rubin, 2003) and require an integrative memory system to merge its features, including e.g., spatial context and experienced emotions (Rubin et al., 2003). In a similar vein, VR experiences deliver episodic features, i.e., temporal and spatial dynamics of an event but beyond that a higher emotional salience and an egocentric reference frame, both contributing to increased self-relevance and self-efficacy (see 3.3).

The formation of AMs under immersive VR conditions has been broadly discussed in both the *free recall study* and the *theta old/new study* (see also Kisker et al., 2021b; Schöne et al., 2019). For this reason, the issue will be summarized only briefly in the general discussion at hand. Nevertheless, it should be particularly emphasized that the intersections between AM's and VR's characteristics indicate that differences between memories of VR experiences and conventional laboratory events are related to the underlying memory systems and, accordingly, promote the differences in the retrieval mechanisms. Specifically, autobiographical memory (AM) is associated with recollection, the vivid and conscious recall of past experiences (Cabeza et al., 2004; Guderian & Düzel, 2005). Conversely, the recall of an immersive VR experience was also associated with recollection, whereas the same events experienced via screen presentation resulted predominantly in familiarity-based recall (Kisker et al., 2021b). In terms of the dual-process theory, recollection is associated with the confident, accurate retrieval of specific details of a remembered event and is therefore often considered to reflect retrieval of stronger memory traces compared to familiarity (Diana & Ranganath, 2011), making a point for the memory superiority effect of VR experiences. However, the dual-process theory is not without controversy and oftentimes contrasted with the single-process theory, which models recognition memory as a continuous process (Pratte & Rouder, 2011; Yonelinas & Parks, 2007). Based upon the signal-detection theory, the single-process theory proposes that a test item is recognized as "old", and is thus remembered, when the respective memory strength hits a decision criterion (Wixted, 2007; Yonelinas & Parks, 2007). Although this theoretical approach does not differentiate between familiarity and recollection, it acknowledges that engrams differ in their strength. Recalled engrams rated as vividly recollected might just score higher on a continuous scale, exceeding the threshold at which it is detected to be "old" even further than those rated as familiar. Accordingly, the increased strength of VR-based engrams compared to conventionally induced engrams argues for the memory superiority effect of VR experiences regardless of the underlying process theory.

The previous association of VR and recollection was based on behavioral data only (Kisker et al., 2021b). Although a higher perceived realism during and better recall of the VR experience argues for the integration of the VR experience into a broader AM network as well (Schöne et al., 2019), more solid evidence is provided by the *theta old/new study*. The absence of the old/new effect in the VR condition and the respective difference in electrophysiological responses to old images are indicative of differences in the underlying retrieval mechanism, albeit not directly linked to recollection. In particular, the effortless retrieval of such multimodal memories might facilitate the sense of reliving a past experience, which goes beyond the engrams formed in classical setups (Rubin et al., 2003). These processes might correspond to the quick, intuitive recall inherent to AM and to a feeling of rightness on the one hand, and to more conscious and elaborate monitoring typical of episodic memory (EM) in case of conventional laboratory events on the other hand (Gilboa, 2004). Whereas the latter might trigger a verification process which is iterative and foremost guided by the visual cue, VR-based engrams might be recalled spontaneously and automatically due to their multimodal patterns (see Study 3; Conway & Pleydell-Pearce, 2000; Willander & Larsson, 2007). As the recollective patterns of VR-based engrams are associated with stronger memory traces (Diana & Ranganath, 2011), they would result from deeper processing in terms of the level of processing theory (Craik & Lockhart, 1972). Consequently, VR's characteristics like sensory richness, altered affective processing, and high personal relevance facilitate the formation of engrams of greater depth, contributing to differences between VR and conventional setups in memory studies.

The previously presented explanatory approaches can principally account for both enhanced memory performance and altered retrieval mechanisms. However, they do not resolve the contradictory results of both studies at hand with respect to memory performance. Thus, inconsistent findings on the memory superiority effect of VR engrams cannot be traced back to the depth of processing alone. Differences in memory performance across studies may possibly result from the various, specific retrieval tasks. Participants performed either an unannounced free recall test (Study 1.2) or an unannounced recognition memory test (Study 3). As free recall is not identical but very similar to recollection (Yonelinas, 2002), recall tasks might benefit to a greater extent from deep VR-based engrams. In contrast, recognition tasks might in general be more strongly driven by familiarity, even if recollection processes occur additionally. Despite many differences between the various dual-process theories, they are consistently assuming that familiarity occurs earlier than vivid recollection (Yonelinas, 2002). By presenting a cue that even offers a multifaceted scene rather than isolated objects (Study 1.2 & 3) the recognition process based on familiarity might be initiated and completed before recollection takes hold, irrespective of the previous presentation mode during encoding.

While this approach might account for the incongruence between the *free recall study* and the *theta old/new study*, it is not sufficient to explain equivalent discrepancies in the larger research context. As illustrated by Table 2, the superior retrieval of VR-based experiences does not correspond to a specific memory task. In particular, the memory superiority effect was evident in some studies applying free recall, cued recall and recognition tasks on the one hand, but absent in other studies applying all the same retrieval tasks and hardware, i.e., head-mounted display (HMD) *versus* desktop (see Table 2, p. 112). In a similar vein, no congruent findings occur when considering incidental *versus* intentional encoding, or when taking the modality of the to-be-recalled stimuli into account. Although the studies listed in Table 2 are only representatives of the respective research background, they demonstrate that keeping the presentation mode the same across studies (VR vs. desktop) does not necessarily produce consistent changes in mnemonic processes.

Table 2.

Overview of VR memory studies focusing on memory performance.

Study	**Task**	**Encoding**	**Recalled stimuli**	**Memory performance**
Free recall study (Schöne, et al., 2021)	free recall	incidental	scenes from video footage (without cue)	HMD > desktop
Theta old/new study (Kisker et al., 2020)	remember/ know task	incidental	scene screenshots from video footage	HMD = desktop
Cadet & Chainay, 2020	free recall	incidental	objects placed within the VE	HMD = desktop
Harman et al., 2017	free recall	incidental	tasks described and performed within VE	HMD > desktop
Kisker et al., 2021b	remember/ know task	incidental	objects placed within the VE	HMD = desktop
Ernstsen et al., 2019	cued recall	incidental	objects placed within the VE	HMD = desktop
Schöne et al., 2019	old/new task	incidental	screenshots from video footage	HMD > desktop
Krokos et al., 2019	cued recall	intentional	pictures depicted within the VE	HMD > desktop
Dehn et al., 2018	free recall	intentional	learning and purchase of shopping list items	HMD = desktop

Note. All studies utilized sophisticated HMDs and compared a VR condition to a conventional desktop condition. This overview is not meant to be exhaustive but provides exemplars of recent VR memory studies applying different retrieval tasks and stimuli.

Beyond varying the retrieval tasks and the recalled stimuli, the underlying memory systems might contribute to these inconsistent findings. As the *theta old/new study* demonstrated, the mode of retrieval differs as a function of the presentation mode during encoding, although stimulus content and retrieval task were held constant, and although both groups performed equally well during retrieval. Taking this up, the superior retrieval of VR experiences might depend on whether the specific characteristics and features of the designed VR suit the to-be-addressed memory system and the applied task. For example, immersive conditions did not promote higher learning performance of a dance either via immersive VR or via a conventional video, whereas a first-person perspective facilitated learning of that dance compared to a third-person view (LaFortune & Macuga, 2016). Similarly, interactive VR applications promote the retrieval of spatial information but not necessarily of factual knowledge. Both the interactivity of VR applications as well as the possibility to plan actions carried out by someone else enhanced spatial memory but impaired factual memory (Plancher et al., 2013). Thus, studies reporting superior memory performance for VR experiences might have involved the memory system under investigation more inherently during encoding. In conventional studies that hold the presentation mode constant between groups, e.g., two conditions using screen presentation, such matching to memory system characteristics would not be noticeable because both groups would be equally affected. In contrast, VR setups allow for more specific adaptions to the (supposedly) operating memory system and particularly the comparison of different presentation modes might reveal related differences. For example, Kisker and colleagues (2021b) found no overall superiority in recognizing objects originating from a previously explored, interactive VR environment. As in Plancher and colleagues' study (2013), the task of exploring the village might have engaged spatial memory more strongly compared to EM or AM. Presumably, the memory performance might have been superior in the VR condition if participants had completed a spatial task instead of the recognition memory test for objects.

In a similar vein, the sensation of presence promoted within VR is considered to improve memory performance (Bailey et al., 2011; Makowski et al., 2017; Smith, 2019). It is assumed that the feeling of presence enhances the attentional focus on the VE (Makowski et al., 2017) and corresponds to more specific and detailed information being processed and stored than under non-immersive conditions (Mania & Chalmers, 2001) which would presumably aid recollection-based retrieval. In the *free recall study* and the *theta old/new study*, participants reported higher feelings of presence, with the significant difference from the PC group in the *theta old/new study* being limited to general and spatial presence. In the *free recall study*, both groups also differed significantly in involvement and realness. Since only the *free recall study* provided evidence for an overall difference in memory performance between groups, the memory superiority effect might result from higher sensations of involvement in, and realness of the VE in this study. In contrast, however, other findings indicate that a high sense of presence actually leads to high cognitive load and thus limits memory performance (Bailey et al., 2011). Continuing the previous line of thought, it might depend on the memory system involved whether and which sub-form of presence is beneficial for the memory performance, e.g., spatial presence for spatial memory, involvement for procedural memory, and so on. Consequently, the utility of VR for memory research seems highly dependent on implementing the properties of the memory system and processes under investigation in the VR design and task.

Overall, even when solely the presentation mode of the stimulus material is varied (3D/360° vs. 2D), various changes occur that have distinct effects on memory performance. However, neither the depth of processing, the sense of presence, the retrieval task and mechanism, nor the memory system under investigation can individually explain the variable findings of previous VR memory studies. Rather, these factors seem to form a complex web that has not yet been sufficiently investigated under immersive conditions to conclusively clarify under what circumstances the retrieval of VR experiences is superior to retrieval of conventional laboratory experiences encoded in the laboratory. In particular, the specific adaptation and integration of VR's characteristics, such as interactivity and sense of presence, to the characteristics of the memory system or process under investigation seem to play a crucial role. Based on the current state of research and the studies at hand, the primary conclusion is that memories arising from VR experiences and conventional laboratory experiences are reflected in distinct retrieval processes and mechanisms. The retrieval of VR experiences reflects many characteristics typical of the AM, suggesting that VR-based memories constitute a more accurate reflection of everyday memories than conventional laboratory ones. Regardless of this assumption, however, it seems plausible that at least one of the presentations modes at hand results in memory processes that are inherent to that mode but not to real-world experiences. Yet to quantify the extent to which this assumption holds true, a triadic investigation of memory for the same experience under real-world, VR, and conventional laboratory conditions is required.

3.5 Embodied Simulations

Across all four empirical studies at hand, changes in three features are apparent irrespective of the corresponding theoretical background, i.e., the approach/avoidance dimension and memory retrieval. In particular, the perception of the experimental situation in a VR setup elicited higher levels of presence, increased self-relevance and corresponded to an egocentric reference frame (see Figure 4, p. 98). These characteristics are intrinsically intertwined in one concept: Embodied simulations (ES; e.g., Gallese & Sinigaglia, 2011; Riva et al., 2019).

In short, embodiment denotes the strong link between cognition and bodily experiences. Higher cognitive functions like understanding a situation are dependent on, and modulated by, biological processes, e.g., sensory and motor experiences, to a high degree (Johnson, 2015). With respect to this notion, ES are a mental simulation of certain representational content like motor actions. This simulated content is directly related to one's own bodily responses, e.g., by simulating other persons' actions to facilitate the understanding of the consequences for oneself or others' intentions behind this action (Gallese & Sinigaglia, 2011).

As Riva and colleagues (2019) pointed out, VR is a simulative technology which is effective as it incorporates mechanisms inherent to the human brain. This assumption is based upon the concept of ES and the predictive coding hypothesis. The predictive coding, or predictive processing hypothesis proposes that the human brain maintains and updates an internal model of the surrounding world at all times. It serves the function of predicting any sensory input and respective consequences and compares both to the actual inputs from, and consequences in the real world. Any errors of these predictions are integrated into the model, allowing constant updates and adaptions of the inner representation (Clark, 2013; Egner & Summerfield, 2013; Friston, 2018). In neuroscience, the hypothesis that this inner model does not only incorporate the surrounding world but also a representation of the own body, also known as the body matrix, gained popularity (Moseley et al., 2012; Riva, 2018; Riva et al., 2019). The body matrix includes sensory input to the body, motor experiences and input from the ANS. Besides actions and their consequences, the matrix envelopes emotions and conceptual knowledge as well. This representation of the self within the inner predictive model renders the simulation an embodied simulation (see Riva et al., 2019).

Building on ES, Riva and colleagues (2019) hypothesized that VR operates in a similar way: The VR system aims to predict and implement the sensory consequences which result from the user's actions within the simulated world. Like a representation of the real world, a model of the VE is predicted, i.e., in technical terms programmed, pre-loaded and rendered. By real-time adaptions, VR technology aims to generate a model of the user's point of view, position and the surrounding world as similar as possible to the brain's predictive model (Parsons et al., 2020). For example, the viewing angle and point of view are updated in response to the user's head movements. Within this framework, the egocentric reference frame and self-relevance are mirrored in the body matrix. Additionally, feeling present in the VE is necessary to track the differences between actually incoming and predicted sensory input (Parsons et al., 2020). Combined in the ES, these features go well beyond what conventional setups can provide. In particular, the perception of a "peri-personal space" (Gallese & Guerra, 2012), i.e., the perception of the environment based on the somatic coordinates of the self, can be easily realized through the egocentric perspective and the sensation of presence in VR setups. In contrast, conventional footage is usually perceived from a third-person perspective and delimited from one's own body matrix, albeit movies can be embodied to some degree as well (Gallese & Guerra, 2012).

However, the assumption that VR and the brain share the mechanism of ES has some flaws. First off, the concept of ES was originally understood as a mechanism contributing to the understanding of others' behaviors and intentions, e.g., in terms of the theory of mind (Gallese & Sinigaglia, 2011). According to the classical understanding, ES explicitly relates to mirror neurons firing in response to observed actions and emotions, i.e., the incoming input is mirrored by means of neural activity to gain a better understanding of it, such as the facial expressions of other persons in a social interaction. "Embodied" in that case implies that body parts, their representations and actions are also decisively involved in what is actually a cognitive process (Gallese & Guerra, 2012; Gallese & Sinigaglia, 2011). Moreover, in the context of VR, embodiment relates to, e.g., a virtual body or avatar, rather than to the surrounding environment (Makransky & Petersen, 2021). Since the mere viewing of interactable objects or the plotting of actions can also engage mirror neurons (Gallese & Sinigaglia, 2011), the transfer of ES to VR simulations does not seem invalid but still mixed in terminology – which does not help to simplify the already hotchpotch-like terminology concerning VR. In a similar vein, embodiment and presence are sometimes mixed up in VR literature. Whereas presence is a state of consciousness, embodiment specifically denotes the perception of the (virtual) body and is often referred to when experimental setups include an avatar (e.g., Kilteni et al., 2012). The sensation of embodiment is thought to result from processing the virtual body like the own physical body. Thus, it rather relates to the illusion to own the virtual body, alike the rubber hand illusion (e.g., IJsselsteijn et al., 2006; Slater et al., 2010), than the sensation of being in a virtual place, i.e., the sensation of presence. Yet depending on the interpretation of embodiment, presence is understood as a subcomponent of embodiment in terms of self-location, as also are a sense of agency and body ownership. However, whether presence is a subcomponent of embodiment, or vice versa, or whether both just share some subcomponents like self-location has not been disentangled so far (e.g., Kilteni et al., 2012; Makransky & Petersen, 2021).

Apart from the terminological confusion, and even more important, particularly the assumption that "VR *shares* with the brain the same basic *mechanism* [emphasis added]" (Riva et al., 2019) is critical in at least two ways. It implies that VR actively generates the inner representation of the surroundings and, even more, updates this representation in response to prediction errors. However, VR is missing parts of the feedback loop proposed by the predictive coding hypothesis. Sophisticated VR systems are indeed capable of proprioceptive matching and in some cases even of respective sensory feedback, e.g., by tactile cues transmitted by the Teslasuit (VR Electronics Ltd., England). These features may indeed be attributed to a feedback mechanism. Nevertheless, VR applications are bound to their programming and will not easily update the representation based on user's feedback beyond movements or controller inputs. Crucially, it is not the same whether the VR environment adapts in response to the user (e.g., the virtual viewing angle is shifted), or whether the brain adjusts the inner model of the environment to the physical environment. Moreover, the basic assumption that presence is necessary to capture the differences between actual incoming and predicted sensory input (Parsons et al., 2020) also leads to severe limitations of this approach. The VR system does not receive feedback from the user's perception. It translates motion but has no way to match whether the adaptation to the motion exactly matches the perception predicted by the user or whether the user feels actually present. Hence, it has no access to the body matrix and inner representation beyond the body's position and movements. For example, if the transmitted VE falters, the VR system will still try to transmit the image as smoothly as possible. However, it will not receive feedback whether the image was perceived as faltering. The crucial difference is thus the update function of VR systems versus the full feedback loop inherent to the brain. The latter function would require a highly sophisticated artificial intelligence combined with autonomic and central nervous system online measures and analyses. An approximation of such a feedback mechanism might be represented by biofeedback during the VR experience. So far such applications have been used sparsely as they require high effort and face technical hurdles (e.g., Cho et al., 2002).

The second key critical aspect continues the notion that VR and *the brain* do not share the underlying mechanism. To clarify, VR does not actively constitute the inner representation or simulation of the surrounding world and body matrix – it is not a "hierarchical prediction machine" (Clark, 2013) equivalent to the brain. Rather, VR shares features of the real-world (see e.g., Bohil et al., 2011; Parsons, 2015) and thus provides the same input to said predictive mechanism that constitutes the inner representation. Hence, the crucial characteristic that renders VR such an effective tool is that it mimics the physical world to a sufficient degree that the brain might predict the same model from both. Thus "VR is able to fool the predictive coding mechanism *used by the brain* [emphasis added]" (Riva et al., 2019) but does not *share* this mechanism. The relevant intersection is therefore between the input from the physical world and VR, not necessarily between the mechanisms underlying VR and the brain. Although VR's ability to translate behavior to updates within the VE shows similarities with the mechanism of ES, it is a tightrope act to claim that VR shares the mechanism inherent to the human brain. So instead of referring to a shared mechanism, it would be more appropriate to refer to a shared mental space instead.

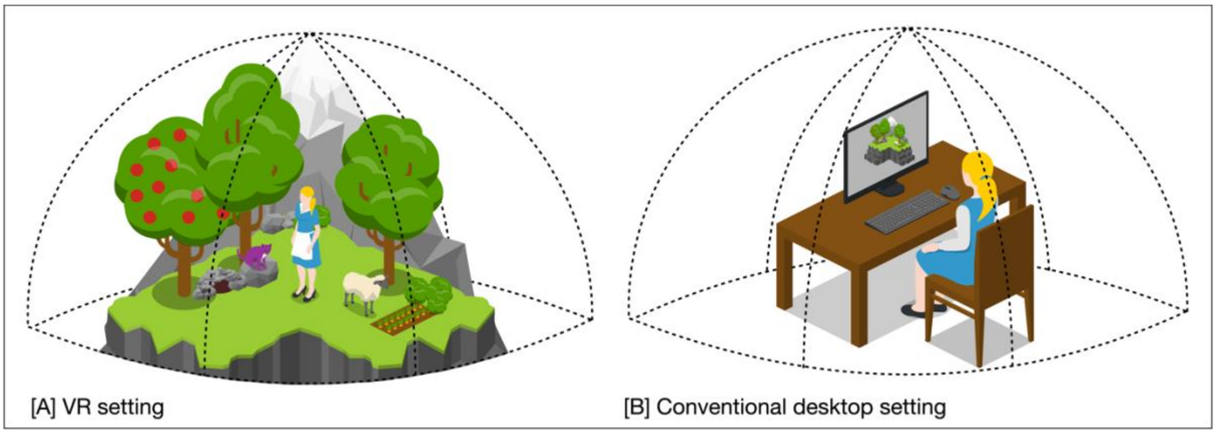
3.6 The 3D default space

Further following the predictive coding hypothesis, VR does not seem to mimic the human brain's mechanism but the input that physical reality delivers to this mechanism. The more similar the input from the real world and from the virtual world are to each other, the higher the probability that they will also feed into the mechanism in the same way and will be similarly processed. As a consequence, the inner simulation of both instances would strongly approximate or overlap each other. The ultimate aim of VR simulations is thus to fool the mechanism constituting the inner representation to form the mental model according to the input delivered by the VR system instead of according to the physical world (Parsons et al., 2020; Riva et al., 2019). As a result, VR simulations fill in an inner recreation of the external space based upon the processed sensory information (Jerath et al., 2015b; Schöne, et al., 2021).This model is based to a great deal on visual input: 80% of all incoming external inputs are processed by the visual system (Jerath et al., 2015b), which might principally give priority to the visual design of the simulation over other sensory elements. Like ES, the 3D default space promotes a first-person experience and thus includes a body matrix as a reference point within the mental space (Jerath et al., 2015a, 2015b). In general, the ES and the 3D default space models both give rise to the assumption that VR replaces the internal representation of the physical environment. Yet in contrast to ES, the concept of the 3D default space specifically refers to a visual mental model within which sensory information are spatially mapped, represented and experienced in a first-person manner. Thus, it does not only refer to individual simulations, e.g., the intentions of an interacting person but is supposed to represent the entire environment and objects, actions, and so forth within it (Jerath et al., 2015a).

While Riva and colleagues (2019) proposed that VR itself "*holds* the mechanism [emphasis added]*"* of ES, VR in terms of a 3D default space *is* an ES: It feeds the predictive mechanism - which remains inherent to the brain - and thus fills in the mental representation. Under this premise, VR functions like a dome put over the user: The physical world is masked out and foremost the visual input is replaced by the stimuli within the hypothetical dome (see Figure 5A, p. 120). The brain has no choice but to fall back on these stimuli to create and maintain the internal model. Particularly the ability to feed the mechanism and fill the inner representation like a dome distinguishes VR experiences from conventional screen experiences. In terms of Brunswik's understanding of ecological validity (Brunswik, 1955; Kihlstrom, 2021; see 1.2), the dome-like replacement of the real input with the virtual input would mean that the "lens" through which the environment is perceived produces less dispersion as the virtual input mimics the real world to an adequate degree (see e.g., Kisker et al., 2021a). Conversely, in a conventional laboratory situation, a stimulus is depicted on a screen. The inner representation of the situation will definitely contain the stimulus. It will be integrated into the model of the overall situation – depicted on a monitor, the participant sitting at a desk within a sterile laboratory. The body matrix thus will be located at a remote distance to the stimulus. While the 3D default space allows for the perception of and interaction with the external world, it will not immerse the viewer into the specific scene depicted on a screen but into the laboratory looking at a screen as depicted in figure 5B. Consequently, in this setup participants would have to actively imagine themselves in the situation shown with less informative cues, e.g., monoscopic cues restricted to a narrow viewing angle, while the VR dome does this automatically without further imagination.

Figure 5.

Mental representation of VR and conventional desktop settings in the 3D default space.



Note. Schematic image of the proposed mental representations of different experimental setups in the 3D default space. Panel [A] illustrates the VR setup in which the VR environment itself occupies the mental space like a dome. Panel [B] depicts a conventional desktop setup in which the stimulus is presented on a screen but does not fill the entire 3D default space.

The inner representation of the external world is thought to be part of the default mode network (DMN; Jerath et al., 2015b). If VR is capable of feeding the mechanism constituting the inner mental model of the physical surroundings, the brain might integrate it into its default processes. Strikingly, recent studies found evidence that VR-based paradigms are indeed capable of modifying the DMN's activity. Seinfeld and colleagues (2021) found evidence that first-person VR experiences modify activations of the DMN, thereby altering emotion recognition concerning ambiguous stimuli. Similarly, Brihmat and colleagues (2018) demonstrated equal activation patterns for the observation of real and virtual hands. The DMN was more strongly involved in imitation tasks than execution or observation tasks. In union, these studies suggest that the modification of the DMN is indicative of introspection and self-processing in response to VR-paradigms (Brihmat et al., 2018; Seinfeld et al., 2021). VR thus yields a more natural processing style compared to conventional settings. Especially the modulation of the DMN in response to ambivalent stimuli may account for the discrepancies between the collected FAA data obtained from the studies at hand (*motivation study* and *cave study*) and previous models. The presentation of the same stimulus material under VR conditions promotes stronger self-referential processing compared to conventional setups, and different responses than watching a video perceived in a remote manner separated from the body matrix. To the same extent, modifications of the DMN might alter mnemonic parameters, as it is, e.g., related to autobiographical memory retrieval (Seinfeld et al., 2021). Consequently, the modification of the DMN in response to VR experiences might account for the diverse outcomes from VR and conventional experimental experiences.

3.7 Amplifier or Game Changer

In theory, VR might be effective in two different ways: On the one hand, it is logical in many respects to assume that VR acts as an amplifier. In this case, established effects would primarily be replicated under VR conditions and amplified due to VR's immersive character. On the other hand, it may be the case that VR applications produce not only quantitatively but also qualitatively different results than conventional settings. The results of the studies at hand strongly indicate that the latter scenario is much more likely.

On a basal level, it seems intuitive that using VR paradigms which constitute higher immersion, presence and interactivity will increase or amplify the cognitive-affective processes at work. In line, several previous studies found increased emotional intensity under VR conditions as compared to conventional conditions (e.g., Gorini et al., 2010; Higuera-Trujillo et al., 2017). VR's ability to elicit congruent and intense emotions is attributed to the strong sensation of actually being within, and part of the VR experience. Across studies, it has been reported that those individuals who felt highly present in VE also reported more intense emotional states (Gorini et al., 2010; Kisker et al., 2021a; Riva et al., 2007). Although this relationship has been broadly studied, its effective direction is still unresolved. Some interpreted the link between high presence and intense emotional responses as indicative that presence is a basic prerequisite without which emotions could not be evoked using VR (e.g., Felnhofer et al., 2015). Conversely, others assume that intense emotions reinforce the feeling of being present in VR (e.g., Diemer et al., 2015). Evidence for the latter assumption was found in both between-subject (Kisker et al., 2021a) and within-subject studies (Gromer et al., 2019) manipulating the VR's affective design. However, studies to date have been correlative, which means that a causal relationship could not be conclusively determined any more than an interaction could be ruled out. In this context, it is not the valence of the emotion that is decisive for the context but rather the level of arousal achieved (Felnhofer et al., 2015). According to the current state of research, it can be assumed that the sensation of presence and the intensity of emotions are mutually dependent on each other.

In a similar line of thought, the memory superiority effect found for VR-based engrams (e.g., Harman et al., 2017; Krokos et al., 2019; Schöne et al., 2019) scores a point for the assumption that VR acts as an amplifier. Even if the superiority effect does not occur under all circumstances, encoding from VR experiences produces at least equally good memory performances compared to conventional setups (e.g., Ernstsen et al., 2019; Kisker et al., 2021b, see also Table 2, p. 112). Immersion and the sensation of presence are proposed to enhance memory performance (Bailey et al., 2011; Makowski et al., 2017; Smith, 2019).

However, the studies that are included in this dissertation demonstrate one thing in particular: It's not that simple. It is downright impossible that VR is merely an amplifier of previously found effects. Especially, but not only the four studies at hand provide evidence that even established effects change in terms of their quality. This is particularly underlined by consideration of the electrophysiological correlates of cognitive-affective processes: Memory performance is not only enhanced (*free recall study*) but the mode of retrieval is altered (*theta old/new study*); emotions are not just more intense (*cave study*) but might exhibit distinct appraisal of the affective experience (*motivations study* and *cave study*) – even if only the mode of presentation is varied (*free recall*, *theta old/new* and *motivation* studies). Similarly, the inconsistency of the results regarding the memory superiority effect indicates that differences resulting from the increase in ecological validity are not linear (see 3.4). As the translation of standard paradigms alters respective effects not only in quantitative but also in qualitative terms, VR is not an amplifier but a game changer. Thus, when translating standard paradigms to VR paradigms, it cannot be assumed per default that the same, well-known effect will occur that was obtained from laboratory conditions. As demonstrated by the studies at hand, VR experiences potentially result in strikingly different outcomes compared to conventional laboratory experiences.

This conclusion ultimately raises the question how real VR is. It needs to be clarified right away that the studies included in this dissertation cannot answer this question. They provide initial hints that VR is more realistically perceived and generates more realistic outcomes than conventional setups. How far the distance between these two and the real world is cannot be concisely determined. However, initial studies venture to unravel this distance between VR and physical reality on a hypothetical reality scale. The majority of these studies investigate VR in direct comparison to physical reality based on a practical background, usually clinical psychological applications like VR exposure therapies (VRET; Gorini et al., 2010, for a review see e.g., Oing & Prescott, 2018). The therapeutic use of VR provides strong evidence that VR applications can produce long-term changes in real-life behavior and cognition (e.g., Opriş et al., 2012). Although it needs to be kept in mind that such findings are based on samples that tend to be extremely responsive to respective aversive stimuli (Cisler et al., 2010), they still deliver initial indicators of the realistic nature of VR experiences. Yet beyond clinical applications, participants' emotional responses to 360° images of a pleasant outdoor scenery equaled their real-world pendant (Chirico & Gaggioli, 2019). Likewise, the perception of virtual height elicited anxiety and reduced balance alike the equivalent real-world situation (Simeonov et al., 2005) and viewing either virtual or real hand movements exhibited the same activation patterns in an fMRI study (Brihmat et al., 2018). Considering these results, the increased ecological validity of VR and the assumption that VR experiences may be perceptually integrated into the DMN like real-world environments (see 3.6), the conclusion seems plausible that VR applications correspond to more realistic outcomes than conventional setups. However, because evidence for the overlap between VR and reality is still sparse, this hypothesis requires in-depth investigation.

3.8 Tabula Rasa

Irrespective of whether VR provides a closer approximation to the real-world compared to conventional laboratory setups or not, the differences found between both experimental settings indicate that at least one of the two does not directly correspond to the real world. Accordingly, it needs to be considered that some of the effects discovered in cognitive-affective research are dependent on the presentation mode and would not equivalently occur in the real world. This limitation accurately reflects Orne's (1962) understanding of ecological validity: If an experiment contains characteristics unique to the experimental setting that have no counterpart in the real world, they cannot be (fully) ecologically valid (Kihlstrom, 2021; Orne, 1962).

However, the conclusion again is: It is not that simple. As previously outlined (see 3.7), it cannot be assumed by default that VR produces more realistic results under all conditions and in all cases. VR results not only in amplified but strikingly different outcomes compared to conventional settings and offers a whole new field of research. Until it is explicitly clarified how real VR is, it cannot be determined whether either experimental setting reflects reality to the fullest possible degree. Previous findings indicate that VR provides a better approximation of the real world due to its higher ecological validity (see e.g., Brihmat et al., 2018; Chirico & Gaggioli, 2019; Simeonov et al., 2005). In particular, assuming that VR activates the DMN (see 3.6), holistic processes may be triggered. A triad is needed to clarify which method produces the more realistic results. To this end, the same experience should be compared between real, VR, and conventional laboratory settings. Furthermore, it would need to be examined whether the results of this triad are replicable - both across experiences and across mechanisms or processes. For example, as demonstrated by the inconsistency of previous VR memory studies (see 3.4), it may well be that VR produces more realistic results only if the specific entity under study - whether memory, emotion or similar - is accurately integrated in the experimental design, e.g., by means of interaction regarding procedural mechanisms or egocentric perspective regarding personal memories.

Under the premise that VR on the one hand produces different results than conventional settings and that these results are on the other hand more alike the real world (see 3.7), one might argue that previous cognitive-affective research is invalidated and back to zero in a tabula rasa manner. However, this position is rather extreme and not true to this extent if reflected critically. On the one hand, and at the minimal level, previous research outcomes deliver a meaningful foundation for VR-based paradigms (see e.g., the *free recall*, *theta old/new* and *motivation* studies). VR studies build on the state of research just as it has always been the status quo. It is through these findings and shared consensus that it is possible to examine differences between previous and VR-based findings and identify potential underlying causes. Furthermore, the differences between conventional and VR conditions do not necessarily mean that the effect found under the former is non-existent. It may only have a smaller, less apparent contribution to its real-world counterpart than derived from isolated conditions (see e.g., Lange & Osinsky, 2020). For example, the FAA data in the *cave study* could not be reconciled with the canonical models on the role of FAAs in terms of approach/avoidance motivation. Nevertheless, it was possible to a limited extent to distinguish those who attempted to escape the threatening situation by retreat towards the former part of the cave from those who advanced towards the exit. Accordingly, FAAs do indeed have a role in the processes that occur in response to an aversive experience. In concert with other processes that occur throughout a realistic experience, they might be modulated by variables that were not yet considered, e.g., behavioral components, or overshadowed to the extent that they do not stand out in isolation and have a lower significance than they do in classical studies (see *cave study* for details).

On the other hand, there are effects that are independent of the setting and have been demonstrated equally in field trials and laboratory studies. For example, flash bulb memories, i.e., the concise recollection of emotionally charged events even years after this event occurred, of 9/11 were found in people witnessing this event. Not necessarily being eyewitnesses, participants are usually able to report detailed information about their location or activity for the time they learned of similar events (Conway et al., 2009). As a side note, recent findings indicate that flash bulb memories are not mandatorily concise – oftentimes, participants' memories of such intense events are false. What is still special about flash bulb memories is the confidence with which participants claim to recall them (Greenberg, 2004; Talarico & Rubin, 2003, 2007). With respect to perceptual psychology, e.g., change blindness is evident in both laboratory studies and naturalistic settings (Simons & Rensink, 2005). Yet not every effect that is prominent can be generalized (e.g., inattentional blindness; Schöne et al., 2021). Thus, VR provides the opportunity to extend previous knowledge. Models and theories can be tested and refined under ecologically valid but controlled conditions and thus enable differentiation of such effects which are potentially generalizable to everyday life and those needing deeper re-evaluation.

Effects that occur equally under both experimental settings indicate high validity of these findings. Consequently, VR does not render all previous research results void but offers the chance to refine them and push the state of knowledge forward. While this dissertation is being written, VR technology is already being further improved. It would be naive to assume that the VR systems described here as sophisticated will not be surpassed by lighter, even higher resolution systems within the next few years. This trend might also be a further leap towards simulated reality. The bottom line is that VR does not render previous research completely void in the sense of a tabula rasa but that it means progress. To say it in Heraclitus words: “There is nothing permanent except change”.

3.9 Ethical considerations and mental borders

Increasingly realistic VR applications are also accompanied by increasing ethical responsibility and novel ethical-moral challenges. Looking at VR from all ethical angles and dealing with corresponding consequences, e.g., how to handle immoral actions of the user within VR, goes far beyond the scope of this dissertation and in-depth discussions can be found elsewhere (e.g., Parsons, 2019; Slater et al., 2020). In the following section, particularly the ethical challenge that is directly related to the studies included in this dissertation will be considered: The intensification of the VR experience compared to conventional experimental settings.

A common argument for the use of VR in research is that VR is thought to be suitable for conducting those studies that would be ethically and morally questionable in a real setting (see e.g., Armstrong et al., 2013; Slater et al., 2006). For physical injury or threats, this may be true – in general, VR cannot inflict physical harm if one disregards poorly adapted physical counterparts in mixed settings or motion sickness. For psychological integrity, however, it may not be so simple. As particularly the *cave study* demonstrated, VR setups are capable to elicit strong emotional responses on a subjective, electrophysiological and foremost behavioral level. The cave experience was certainly more intense as compared to a screen experience, although no PC condition was obtained. Even if the users are unaware of it, their behavior is strongly impacted by external factors (Madary & Metzinger, 2016), including the respective VR environment as demonstrated by the effectiveness of VRET (e.g., Botella et al., 2017; Marquardt et al., 2018). However, changes in response to VR experiences, whether emotional, cognitive, or behavioral, are not necessarily positive ones. Likewise, harmful changes can occur (Dibbets & Schulte-Ostermann, 2015; Slater et al., 2020). Although it has sparsely been systematically studied (e.g., Dibbets & Schulte-Ostermann, 2015), after-effects are often reported as anecdotal evidence, e.g., in the form of long-lasting frights (Lin, 2017) or nightmares (*cave study*) after negative or frightful VR experiences. Similarly, the memory system might be deceived to such an extent that, especially after very realistic experiences, users can no longer separate which experiences were real and which ones were virtual in the long term (Slater et al., 2020).

Under the premise that VR generates very realistic (Kisker et al., 2021a), possibly even reality-equivalent experiences (Brihmat et al., 2018; Chirico & Gaggioli, 2019; Simeonov et al., 2005), the studies ethically and morally questionable in real-world settings are de facto equally questionable in VR. As "torture in a virtual environment is still torture" (Madary & Metzinger, 2016), the golden rule of non-maleficence should be respected to the same extent as in real-world settings.

Nevertheless, there has to be a narrow level of dissonance between emotion and cognition that leads to a certain meta-awareness that the experience is "only" a virtual one (e.g., Schubert et al., 2001). Slater (2020) describes this dissonance as "knowing it is not real but feeling it as if it were". For example, participants in the studies using VR footage must have been aware to some degree that the experience was not real due to the rapid change of stimuli or the inability to move through the scene beyond head-tracking. Similarly, the fictional werewolf in the *cave study* was a clear indicator of the experience not being real. The same holds true for studies that require participants to cope with high physical risk they would not take in real-life situations, like balancing unsecured at great heights (e.g., Kisker et al., 2021a). In terms of the "quick and dirty" pathway of emotional processes (e.g., LeDoux, 1995, 1996, 2014), it is intuitive to react to a situation first, e.g., to escape a threat triggered by bottom-up processes, and to engage in cognitive coping mechanisms only afterwards, like top-down self-calming strategies (e.g., Lin, 2017; Lin et al., 2018).

Thus, the response to a VR environment, whether emotional, electrophysiological or behavioral, can be realistic albeit participants not being convinced to the fullest possible degree that the experience is or was real (Slater et al., 2020). This fine line may lessen the concern of ethical and moral trials in VR compared to reality to some degree. However, the more this mental border between VR and reality fades, e.g., through increasingly better technology and realism, the more carefully ethical and moral aspects need to be considered when using VR as an experimental tool. In principle, it has to be anticipated that even ethically ambiguous VR applications will find their way into everyday life, e.g., in the form of entertainment. Thus, the investigation of the cognitive-affective foundations underlying such applications gains even higher priority.

3.10 Concluding remarks

The aim of this dissertation and the included empirical studies was to shed light on whether and which changes in cognitive-affective standard findings result from increasing the ecological validity of psychological research by means of VR paradigms. To this end, cognitive-affective standard paradigms were translated from conventional laboratory setups to immersive VR conditions.

The four empirical studies that are included in this dissertation demonstrate in particular that effects found in previous research are not just amplified under immersive VR conditions. Not only the quantity of corresponding standard research outcomes changes under conditions of higher ecological validity but also their quality: The emotional response triggered by the VR experience is not only more intense but can vary in its quality to the extent that even opposite emotional-motivational tendencies are possible under VR conditions compared to conventional conditions. These differences in emotional quality can be traced back, among other factors, to an altered appraisal of the situation. The increased self-relevance and interactivity of VR facilitates active, emotional engagement going beyond experiences of conventional screen-based events (see 3.3). Moreover, VR-based memories are oftentimes, but not always, better, i.e., more frequently and accurately recalled than those of laboratory-induced experiences. Rather, the underlying retrieval is altered, so that the superiority of these memories emerges only under specific conditions. It has been speculated that the superiority of VR-based memories can be traced back to deeper processing of the VR experience and occurs particularly if the underlying memory system is specifically mirrored in the implemented VR characteristics. However, this speculation alone, as well as further influences, can neither individually nor conclusively account for the inconsistencies regarding the memory superiority effect (see 3.4).

Deviations from standard settings and findings that are equivalent across all four studies - such as an increased sense of presence and self-relevance, along with an egocentric reference frame - are attributed to the assumption that VR and reality share a 3D default space. Immersive VR experiences deliver realistic input to the sensory channels and to the predictive mechanisms of the brain in such a way that the mental model computed from this information might overlap to a large extent with the mental model computed from physical reality. In terms of a body matrix, the representation is constructed on the basis of the somatic coordinates of the self and thus enables an egocentric reference frame within the mental representation. Consistent with previous studies, VR experiences are integrated into the DMN and thus processed more naturally than, e.g., screen-based experiences (see 3.5, 3.6).

Regardless of whether the changes resulting from increases in ecological validity suggest that VR elicits more natural, realistic processes and mechanisms, they indicate that some effects, even very well-established ones, are in part dependent on the mode of presentation during the experimental situation. This dependence contradicts the notion of ecological validity that experiments should not hold factors that are typical of the setting but not of reality (Kihlstrom, 2021; Orne, 1962). From this consideration arises the chance to increase the generalizability of psychological research by a great deal: VR-based research does not completely render previous findings void but provides an ecologically valid and at the same time controllable method to give cognitive-affective research a touch up. Such effects that occur equally under conventional and VR conditions would have an absolutely superior generalizability to those that are inherent to only one of both methods (see 3.7, 3.8).

Endless new questions arise from this new field of research. The most obvious, but also most relevant question is how real VR actually is. Although initial studies indicate that responses to VR and real conditions strongly overlap (Chirico & Gaggioli, 2019; Simeonov et al., 2005), it is unresolved whether this holds true in general, or only for specific processes and mechanisms. For example, the meta-awareness that a VR experience is not real but feels real (e.g., Kisker et al., 2021a; Schubert et al., 2001; Slater et al., 2020), might more strongly increase the realism of triggered bottom-up processes under VR conditions, such as momentary affective reactions compared to top-down processes, as reflected in coping mechanisms (see 3.9). As previously discussed, it takes triads of real, VR, and PC experiences to accurately determine which experimental method is closer to reality.

Accordingly, VR as an experimental method not only opens up a whole new field of research in itself but should also trigger a wave of replication of previous findings under ecologically valid conditions, contributing to the extension and refinement of the understanding of real-world cognitive-affective processes and mechanisms. Based on the four empirical studies at hand and their integration into the existing research body, the following can be said confidently in conclusion:
Virtual Reality is not an amplifier but a game changer.

4. References

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5. Appendix

5.1 Statement of autonomy [German language]

Ich erkläre hiermit, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet. Folgende Personen haben an den Studien und der Erstellung der Publikationen mitgewirkt.

Publikation 1 / Studie 1.1 & 1.2

Rahmentext: Benjamin Schöne (BS)

Studie 1.1:

Entwicklung des Studiendesigns: **Joanna Kisker (JK)**, BS, Rebecca S. Sylvester (RS), Elise L. Radtke, Thomas Gruber (TG)

Datenerhebung: **JK** und RS mit Psychologie-Studierenden der Universität Osnabrück

Konzeption der Auswertung: **JK**, BS, Feedback von TG

Durchführung der Auswertung: **JK**, Feedback von BS, TG

Manuskripterstellung: BS (Einleitung & Diskussion), **JK** (Methoden & Ergebnisse), Feedback und Einverständnis aller Koautor:innen

Studie 1.2:

Entwicklung des Studiendesigns: **JK**, TG

Datenerhebung: **JK** mit studentischen Hilfskräften der Allgemeinen Psychologie I und Psychologie-Studierenden der Universität Osnabrück

Konzeption der Auswertung: **JK**; Feedback von BS, TG

Durchführung der Auswertung: **JK**; Feedback von BS, TG

Manuskripterstellung: BS (Einleitung & Diskussion), **JK** (Methoden & Ergebnisse), Feedback und Einverständnis aller Koautor:innen

Publikation 2/Studie 2:

Entwicklung des Studiendesigns: **JK**, BS, TG, Leon Lange (LL), Roman Osinsky (RO), Kira Flinkenflügel (KF), Michael Kaup, Falk Tetenborg, Nils Labersweiler, Paula Ott, Christopher Gundler

Datenerhebung: **JK**, LL und KF mit studentischen Hilfskräften der Allgemeinen Psychologie I, studentischen Hilfskräften der Differentiellen Psychologie und Psychologie-Studierenden der Universität Osnabrück

Konzeption der Auswertung: **JK,** BS, LL; Feedback TG, RO

Durchführung der Auswertung: **JK**, LL; Feedback von BS, TG, RO

Manuskripterstellung: **JK** (initiales Manuskript, Review-Prozess), LL (Überarbeitung des initialen Manuskripts); Feedback und Einverständnis aller Koautor:innen; **JK** und LL teilen die Erstautorenschaft

Publikation 3/Studie 3:

Entwicklung des Studiendesigns: **JK**, BS, TG
Datenerhebung: **JK** mit studentischen Hilfskräften der Allgemeinen Psychologie I und Psychologie-Studierenden der Universität Osnabrück
Konzeption der Auswertung: **JK,** BS; Feedback von TG
Durchführung der Auswertung: **JK**; Feedback von BS, TG
Manuskripterstellung: **JK**; Feedback und Einverständnis aller Koautor:innen

Sascha Fortmann und Rebecca S. Sylvester (RS) haben auf Rechtschreibung und Grammatik bezogenes Feedback zum Rahmentext dieser Dissertation gegeben. Weitere Personen waren an der inhaltlichen materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder andere Personen) in Anspruch genommen.

Niemand hat von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen. Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Osnabrück, den ....
(Ort, Datum) Joanna Kisker

5.2 Supervision

Primary supervisor: Dr. Benjamin Schöne

Dr. Benjamin Schöne is the primary supervisor of the doctoral studies included in this dissertation as the VR project leader of the department.

Primary examiner: Prof. Dr. Thomas Gruber

Prof. Thomas Gruber is the primary examiner and second supervisor of the doctoral studies as the head of the department.

5.3 List of abbreviations

The order of the abbreviations corresponds to the order in which they first appear in the text.

VR - Virtual Reality

VRET - Virtual Reality Exposure Therapy

HMD - Head-Mounted Display

VE - Virtual Environment

MR - Mixed Reality

IAPS - International Affective Picture System

IADS - International Affective Digitalized Sounds

ANS - Autonomic Nervous System

SCR - Skin Conductance Response

HR - Heart Rate

FAA - Frontal Alpha Asymmetry

CAVE – Computer Aided Virtual Environments

EM - Episodic Memory

AM - Autobiographical Memory

luVRe - Library for universal Virtual Reality experiments

CNS - Central Nervous System

PTSD - Post-Traumatic Stress Disorder

ES - Embodied Simulations

DMN - Default Mode Network

5.4 A technical view on VR

5.4.1 A Tribute to Virtual Reality's Roots

While the foundations of today's VR technology are frequently traced back to Ivan Sutherland (Sutherland, 1965, 1968), even earlier presentation forms and technologies can be found that were considered a kind of VR at their time. Early installations can particularly be found in art. As early as the 18th century, the first circular panoramic images by Robert Barker (1787) became a mass entertainment (Belisle, 2015; Lescop, 2017). From a platform surrounded by a grand circular canvas, the viewer perceived the panoramic painting as if he was standing within the scene. Remarkably, the artist thus made use of VR features that are fundamental to today's VR technology; 360° view and the feeling of being in the scene. Such installations would not correspond to today's understanding of VR, but illustrate how people have long aspired to create alternate realities that would captivate them.

Technical advances of the 20th century rather fit today's notion of VR. As early as the 1950s, Morton Heilig developed the so-called Sensorama (Heilig, 1962). Aiming to create a 4D cinema experience, it made use of stereoscopic view, fans, odor diffusers, and kinetic seats. However, the Sensorama's production was soon abandoned. In retrospect, it seems surprising that most researchers currently engaging in VR technology never heard of the Sensorama, taking into account that it already included essential elements of today's VR technology. Heilig also designed and patented an HMD but never built the prototype (Heilig, 1960; Lescop, 2017). Since it did not enable head-tracking or other interactive elements, it was not considered the first genuine VR headset by most tech experts. The real breakthrough in VR headset development was achieved by Sutherland - his HMD was the first to implement both stereoscopic vision and head-tracking (Mazuryk & Gervautz, 1996; Sutherland, 1968). However, the headset never left the laboratory - it was too heavy and bulky for private use. The first VR equipment that was actually brought to the market was developed by the VPL Research Inc, founded by Jaron Lanier and Thomas Zimmermann (Mazuryk & Gervautz, 1996; Slater & Sanchez-Vives, 2016). From then on, the hopes and possibilities of VR's applications and further development sprouted like weeds. The gaming industry in particular jumped on the new technology, as Nintendo did in 1995 with the virtual boy. However, the product flopped woefully due to low sales numbers (Boyer, 2009). Hence, just as quickly as the beginning of a new era was proclaimed, VR disappeared from the scene again

(Slater & Sanchez-Vives, 2016). One of the reasons for the quick departure from the stage might have been that the hardware was built on a generation of technology substantially different from modern devices – the HMDs offered poor graphics, were both bulky and heavy, and irrationally expensive. This might also have contributed to VR not being widely but only very selectively applied as a research method at the time. Although the aforementioned milestones are just some remarkable examples of many more technical advances, VR has been thought to be "dead" for more than 20 years (Slater & Sanchez-Vives, 2016). It wasn't until 2016 that VR re-emerged on the scene, gaining more and more interest after, e.g., Mark Zuckerberg purchased Oculus and several high-quality, relatively affordable headsets (e.g., HTC Vive, Oculus Rift) were released (Cipresso et al., 2018, see also Cadet & Chainay, 2020).

5.4.2 Differentiation of current Virtual Reality Systems

Due to the broad and varying definitions of VR, there are several groups of devices and software grouped together and associated with the label. For naive laymen, the impression may arise that all available hard- and software create VR in the same way and quality but there are major differences among them (for a review see e.g., Smith, 2019; Takac et al., 2021). Modifications of the technical composition of VR might have decisive effects upon the virtual experience and thus on the research outcome. As a result, VR research - albeit increasingly broad - is currently more of an unorganized patchwork of studies with limited comparability. This significantly hinders replication and integration of the findings into the wider research body.

In general, VR requires a software enabling the creation and design of the VE itself, and a hardware to present and mediate it (Riva, 2006). Essentially, there are two options to create a VE: Firstly, specialized cameras allow to record panoramic, and in some cases even stereoscopic photos and videos (hereinafter both referred to as VR footage). The peculiarity of these cameras lies in their omnidirectional lenses, which, depending on the camera model and the number of lenses, enable the computation of a 360° view or even 3D-360° view (e.g., the Insta 360 Pro by INSTA360, Taiwan). Hence, photorealistic VEs can be easily created by capturing diverse real-life environments. This type of VE eliminates the challenge of animating, e.g., living creatures or, in case of videos, dynamic events.

However, they sacrifice interactivity: The options to present VR-footage are usually limited to directional head-tracking, since the footage is taken from a static point of view (see Serino & Repetto, 2018).

Alternatively, VEs can be computer-generated using gaming software, e.g., like Unity (Unity Technologies, USA) or Unreal Engines (Epic Games Inc., USA). Given the resources and skills to create a programmed VR environment, there are basically no limits to its design and functions (Riva, 2006). Virtual objects can be moved or used, and natural operations can be performed, e.g., picking up a key to unlock a door and walking through it. Although corresponding software offers a mostly intuitive user interface, advanced programming skills are required, making the creation of these environments a more challenging and time-consuming task compared to capturing VR footage. Hence, although both options have advantages and disadvantages, the choice of method particularly depends on whether photorealism or sophisticated interactivity is of greater value for the specific study design.

Both kinds of VEs can be accessed by means of various hardware devices. Currently, scientific literature predominantly differentiates between so-called headset-VR, simulator-VR and desktop-VR systems (Smith, 2019). Headset-VR refers to HMDs or colloquially “VR goggles”. Current HMDs consist of two LCD displays in a mount (relatively) similar to diving goggles. This setup allows to position the displays directly in front of the eyes, with each eye looking at a separate display. By presenting slightly different images on both displays, a three-dimensional view is created. Most current HMDs enable tracking of the velocity and angle of head-movements, enabling a match between the user’s physical and virtual head-movements and view (Slater & Sanchez-Vives, 2016). Hand-held controllers are visually represented within the VE and improve motion tracking, enable locomotion via controller inputs and interactions with the VE, e.g., grabbing virtual objects. Advanced systems even provide hand tracking and/or motion tracking in terms of physical locomotion through a delimited space. Hence, users can naturally move through and interact with(in) the VE (Smith, 2019; Sousa Santos et al., 2009). Less sophisticated systems can easily be created by using smartphones with corresponding adapters (Smith, 2019). On the downside, most VR-headsets offer only limited peripheral vision and some cause motion sickness (Kim et al., 2012; Sharples et al., 2008). However, sophisticated headset-VR is currently becoming more affordable and comfortable (Parsons, 2015), technically advanced and mobile, i.e., many producers provide wireless versions. Due to these qualities, headset-VR is increasingly preferred over other systems in psychological research (see e.g., Bernardo et al., 2020).

In contrast, simulator-VR systems use up to six, but commonly less, external monitors and specialized input devices (Kim et al., 2012; Smith, 2019). Instead of cutting the user off from the physical world by bringing the displays as close as possible to the eyes, so-called *Computer Aided Virtual Environments* (CAVE) setups enclose the user by creating a room which has displays as walls (Kim et al., 2012; Smith, 2019). Specified projectors project different images to these displays, thereby enveloping the user who can freely move within the area bounded by the displays (Smith, 2019). Head- and hand-tracking can be implemented (Kim et al., 2012) and stereoscopic view can be created, e.g., through 3D glasses or multiple projections to the walls (Smith, 2019). Even more, real objects can be integrated into the environment, like cars for driving simulations. Such CAVE systems can cost millions and are completely static, thus rendering them economically impractical. Less high-quality setups can be achieved by using and arranging smaller (3D) screens in an U-shape (Smith, 2019). However, setups only partially surrounding the user deviate from CAVEs in too many characteristics to call them equivalent.

Both headset-VR and simulation-VR can be extended in such a way that they are referred to as mixed reality (MR) or augmented reality (AR). Unlike VR setups, it is intentional in MR and AR that users perceive both, real-world and virtual elements, as if they coexisted in the same space (Costanza et al., 2009; Speicher et al., 2019). More specifically, AR is oftentimes used as an addition to physical environments which are augmented by virtual objects – with the physical world still being predominantly perceived (Carmigniani et al., 2011). In contrast, MR definitions do not specify the dominance ratio between real-world and virtual objects; however, MR often denotes such environments in which the virtual world predominates but is complemented by real-world components. For example, some studies add a haptic dimension to their VR setups by aligning physical objects, e.g., wooden planks to walk across or to mimic stairs (Asjad et al., 2018; Biedermann et al., 2017). Both forms of simulated reality require that physical and virtual elements are precisely matched, especially in terms of their position and size in space (Costanza et al., 2009), which is oftentimes a major technical hurdle.

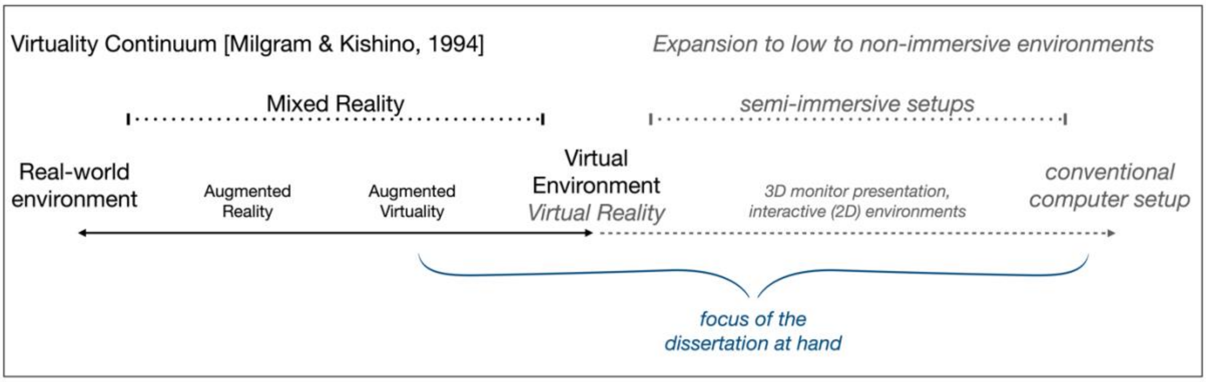
Further setups which are at least partially referred to as VR are so-called desktop-VR setups. Desktop-VR makes use of conventional PC monitors and input devices, e.g., mouse, keypad and joystick (Smith, 2019). They correspond to conventional setups used in psychological research. Although the corresponding VEs are oftentimes created three-dimensionally, they are usually displayed on monoscopic monitors. Some attribute the use of 3D screens to desktop-VR instead of simulator-VR, but the transition here is fluid and rather blurry (see Kardong-Edgren et al., 2019; Takac et al., 2021). Moreover, physical movements and actions do not translate to the VE one-to-one but create a mismatch between the actual action, e.g., pressing a button, and the to-be-reflected action, e.g., turning around (Smith, 2019).

Ranking aforementioned VR forms based on their immersiveness, some researches consider the labeling of desktop setups as desktop-VR inappropriate, among other reasons due to reduced immersion and less degrees of freedom (e.g., concerning head-tracking) compared to sophisticated VR systems (e.g., Takac et al., 2021). The taxonomy of VE's has long been fuzzy, as evidenced by Milgram and Kishino's (1994) early proposal to organize the real-world, VR, MR and AR on a virtuality continuum (see Figure 6, p. 162). The real world and fully immersive VEs formed the opposite poles. Everything in between, including AR, was referred to as MR. In order to fit today's VR taxonomy, this continuum needs to be extended (see e.g., Takac et al., 2021), setting conventional computer setups as the antipole to real-world experiences. On this extended virtuality continuum, VR takes a position between real-world and conventional computer experiences, for which it is not yet defined what effective distance it has from both antipoles (see Figure 6, p.104). The same holds true for semi-immersive setups, such as interactive 2D games or 3D monitors, which lie between VR and conventional desktop applications.

Consequently, in the context of this synopsis and the related studies only sophisticated VR systems, i.e., headset-VR and simulation-VR are referred to as virtual reality. Desktop-VR settings are referred to as conventional laboratory settings or conventional computer settings further on. For the empirical studies, headset-VR was used because current HMDs are among the most technically advanced systems, allowing for high immersion and interactivity, and at the same time outperforming simulator-VR in economic value.

Figure 6.

Extended Virtuality Continuum.



Note. The *Virtuality Continuum* according to Milgram and Kishino (1994; black standard font), extended and adapted to conventional computer setups (grey italics). The continuum is adapted with real-world experiences and desktop settings as antipoles. The arrangement corresponds to an ordinal ranking based on the systems' immersiveness. The distance of the components on the continuum has no quantitative meaning. Adapted and modified from Milgram & Kishino (1994).