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REVIEW

Eye Tracking Studies Exploring Cognitive and Affective Processes among Alcohol Drinkers: a Systematic Review and Perspectives

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Abstract

Acute alcohol intoxication and alcohol use disorders are characterized by a wide range of psychological and cerebral impairments, which have been widely explored using neuropsychological and neuroscientific techniques. Eye tracking has recently emerged as an innovative tool to renew this exploration, as eye movements offer complementary information on the processes underlying perceptive, attentional, memory or executive abilities. Building on this, the present systematic and critical literature review provides a comprehensive overview of eye tracking studies exploring cognitive and affective processes among alcohol drinkers. Using PRISMA guidelines, 36 papers that measured eye movements among alcohol drinkers were extracted from three databases (PsycINFO, PubMed, Scopus). They were assessed for methodological quality using a standardized procedure, and categorized based on the main cognitive function measured, namely perceptive abilities, attentional bias, executive function, emotion and prevention/intervention. Eye tracking indexes showed that alcohol-related disorders are related to: (1) a stable pattern of basic eye movement impairments, particularly during alcohol intoxication; (2) a robust attentional bias, indexed by increased dwell times for alcohol-related stimuli; (3) a reduced inhibitory control on saccadic movements; (4) an increased pupillary reactivity to visual stimuli, regardless of their emotional content; (5) a limited visual attention to prevention messages. Perspectives for future research are proposed, notably encouraging the exploration of eye movements in severe alcohol use disorders and the establishment of methodological gold standards for eye tracking measures in this field.

Keywords Eye movements · Eye tracking · Attentional bias · Visual attention · Alcohol · Heavy drinking · Alcohol use disorders

Introduction

Alcohol use and misuse constitute major public health concerns, leading to a vast range of adverse health consequences (WHO, 2018) and being directly responsible for three to 8 % of deaths worldwide (Navarro et al., 2011; Rehm et al., 2009). Alcohol intoxication has a well-established negative impact on cognition and brain functioning (e.g., Bjork and Gilman,

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2014; Field et al., 2010). Aside from acute alcohol consumption, the fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5, American Psychiatric Association, 2013) proposes the diagnosis of alcohol use disorder (AUD). This approach promotes a dimensional perspective (as AUD can be mild, moderate, or severe according to the number of criteria met among the 11 described) in comparison with the categorical one followed by DSM-IV (distinguishing alcohol abuse and alcohol dependence). The massive consequences of severe AUD on neurocognitive functioning are widely established, and this condition is a major cause of death and disability (Stavro et al., 2013; Wechsler et al., 1995). Recent research has moreover shown that other excessive alcohol consumption patterns (e.g., heavy drinking, hazardous drinking), and notably those frequent among young people (e.g., binge drinking), are related to impaired cognitive and brain structure/function, even when mild AUD criteria are not met (Hermens et al., 2013; Jacobus and Tapert, 2013; Jones et al., 2018). Even moderate alcohol consumption appears linked to neurocognitive deficits (e.g., Anderson et al., 2012; Topiwala et al., 2017). As a whole, alcohol consumption behaviors, even at subclinical levels, are associated with psychological and cerebral impairments.

The dual-process model currently dominates the theoretical conceptualization of the impairments related to alcohol consumption. This model (e.g., Mukherjee, 2010; Wiers et al., 2007) centrally postulates that efficient decision-making is determined by the balance between a “reflective system” (mostly relying on frontal regions and responsible for the deliberative and controlled responses) and a “reflexive system” (mostly relying on striatal/limbic regions and initiating the automatic/appetitive behaviors). In this view, excessive alcohol consumption is related to a disequilibrium between systems: the under-activation of the reflective system generates reduced executive control, while the over-activation of the reflexive system induces increased automatic reactivity to alcohol cues (Noël et al., 2013; Wiers et al., 2013). A large amount of neuropsychological, neurophysiological, and neuroimaging data support this proposal. First, it has been shown that severe AUD, but also subclinical alcohol consumption, are associated with a reduced efficiency of the reflective system, characterized by structural and functional modifications of the (pre-)frontal regions underlying controlled behaviors (e.g., Bühler and Mann, 2011; Carbia et al., 2018; George et al., 2004). These deficits lead to impaired high-level cognitive abilities like memory and executive functions (Bernardin et al., 2014; Stavro et al., 2013). Second, increased activity of the reflexive system has been documented, notably related to changes in limbic regions and the reward system’s reactivity (Koob, 2014; Volkow and Baler, 2015). This results in the augmented salience of alcohol-related cues, leading to craving and attentional bias towards alcohol (Fadardi et al., 2016; Flaudias et al., 2019). Beyond the dual-process model, the most influential models of addictive disorders (e.g., Everitt et al., 2008; Lewis, 2018; Volkow et al., 2016) jointly underline the existence of an increased salience of addiction-related cues (related to an over-reactivity of the reward system), as well as the influence of such cue salience in the development of these disorders. Particular emphasis is thus placed on incentive salience: repeated alcohol exposures lead to a sensitization of the reward system, subsequently enhancing the incentive-motivational properties of alcohol-related cues (Robinson and Berridge, 1993). Becoming more salient, these cues capture and hold consumer’s attentional resources. This preferential allocation of attention towards alcohol-related stimuli further increases subjective craving and approach behaviors, fostering alcohol use.

Neuroscientific approaches are key contributors for renewing the exploration of alcohol consumption’s consequences. Among the techniques recently used to deepen the theoretical understanding of alcohol consumption, a recent surge of interest has emerged for eye tracking measures. This method, presenting a high temporal resolution, capitalizes on the detection of gaze direction to infer links between eye movements and the related brain or cognitive functions. It thus offers complementary insights to those provided by electrophysiological or neuroimaging techniques (Luna et al., 2008). Various eye movements can be indexed, among which fixations (i.e., maintenance of the visual gaze on a specific location), saccades (i.e., coordinated movement of both eyes from one fixation point to another) and smooth pursuit (i.e., following a target moving in a predictable way) are particularly relevant in assessing cognitive processes (Leigh and Kennard, 2004; Lisberger, 2010). Visual acuity is heterogeneous across the visual field: the fovea presents the highest visual acuity and offers the sharpest vision. Saccadic eye movements allow bringing peripheral visual stimuli to the fovea for fine-grained visual analysis. Visuomotor and perceptive processes can thus be indexed by the amplitude, velocity or duration of these saccades (Leigh and Kennard, 2004), while shifts of visual attention are explored through saccade direction measures. Such attentional shifts can be goal-directed (voluntary) or stimulus-driven (involuntary), these systems interacting during perception while being sustained by partially segregated brain networks (Corbetta and Shulman, 2002). When visual objects are moving, smooth pursuit keep them on the fovea. Foveal fixations are considered as points of overt attention, the direction of the gaze being tightly linked to attentional focus (Deubel and Schneider, 1996). Saccade direction and latency thus inform about the initial orientation of attention, while fixation duration and the overall dwell time spent looking at a specific location reflect attention engagement and maintenance, respectively. The number of foveal fixations also informs about attentional reengagement. Overall, eye tracking appears as a very promising tool, allowing to directly and precisely measure the consecutive steps involved in cognitive processing, and thus extending the understanding of the related core processes (Popa et al., 2015). Unlike standard behavioral measures (e.g., reaction time, accuracy rate) that only inform on the final processing output, the eye tracking technique provides major insights on the time course of cognitive processing. The eye tracking methodology is, therefore, widely used to assess attention and visual perception, but it can also explore higher-level cognitive processes like memory or executive functions (Eckstein et al., 2017; König et al., 2016). For instance, spatial working memory is evaluated through the ability of participants to perform saccades towards the locations of previously memorized targets (Paolozza et al., 2013, 2014). The links between attention and long-term memory are also investigated by analyzing the scanpaths of participants looking at pictures that they will have to recall later on (Harvey et al., 2013a, 2013b). In the same vein, inhibitory abilities are measured with the prosaccade/antisaccade task (e.g., Munoz and Everling, 2004), by comparing the ability to perform saccadic eye movements towards a visual stimulus (in the prosaccade condition) or away from it (in the antisaccade condition, measuring the inhibition of the reflexive saccade towards the target). Of note, several studies have used eye tracking to investigate emotional processing (e.g., Calvo et al., 2008; D'Hondt et al., 2016; Fernández-Martín and Calvo, 2016; McSorley and van Reekum, 2013; Niu et al., 2012; Nummenmaa et al., 2006) or emotional facial expression analysis (e.g., Calvo and Nummenmaa, 2008, 2009; Eisenbarth and Alpers, 2011; Jack et al., 2012; Schurgin et al., 2014). While this assumption is still debated, several researchers (e.g., McAteer et al., 2015) even suggested that eye tracking allows dissociating automatic and controlled processes. The automatic processes are in this view measured through first saccadic latency (i.e., the time between stimulus onset and the start of the first recorded saccade) and the first explored area of interest (i.e., the first zone of the stimulus to be targeted by a fixation). The controlled processes are indexed by the total number of fixations on each part of the stimulus (i.e., number of times a saccade has been oriented towards this part) and the dwell time (i.e., total time spent staring at each part of the stimulus). Such dissociation is relevant to test the dual-process hypothesis applied to alcohol consumption.

Eye tracking thus offers an efficient tool to deepen the behavioral and neuroscientific measures of cognitive processes, from basic perceptive abilities to high-level functions. This technique has been used among alcohol drinkers, but with large variations regarding the characteristics of the experimental sample, the cognitive processes measured, and the selection of eye movements' indexes. We present the first integrative review of this research field. Indeed, in the last decade, many review papers have focused either on behavioral studies exploring alcohol-related cognitive impairments, including perceptive processing (e.g., Creupelandt et al., 2019), attentional bias (e.g., Field and Cox, 2008), inhibitory control (e.g., Bernardin et al., 2014; Smith et al., 2014), and emotion (e.g., Donadon and Osório, 2014; Le Berre, 2019) or on neuroimaging studies exploring alcohol-related brain correlates (e.g., Schulte et al., 2012; Sullivan et al., 2010). Nevertheless, none has yet provided an overview of studies using the eye tracking technique among alcohol drinkers, while these studies provide a more reliable assessment of cognitive processes than those using classical behavioral methods (Christiansen et al., 2015a) and complementary insights to those offered by neuroscientific techniques (Luna et al., 2008). The present paper thus proposes a comprehensive and systematic review of all studies exploring alcohol consumption's influence on eye tracking measures.

Methods

Articles Identification and Selection Procedure

We used the PICOS procedure (Population, Intervention, Comparator, Outcome, Setting; Liberati et al., 2009) to determine the inclusion criteria, as follows: (1) Regarding the Population, only studies on human samples were considered, and they had to include (a) participants identified as presenting excessive alcohol consumption, as determined through standardized diagnosis tools (e.g., DSM-V criteria for alcohol use disorders) or through alcohol consumption measures with validated cut-offs [e.g., score higher than 7 at the Alcohol Use Identification Test (AUDIT, Saunders et al., 1993), indexing risky consumption], or (b) a valid measure of participants' alcohol consumption [e.g., AUDIT; Timeline Follow-Back (TLFB, Sobell and Sobell, 1992)] and the inclusion of this measure as a main variable in the analyses. We thus excluded animal studies and studies in which alcohol-related measures were only considered as control variables, but there were no exclusion criteria related to participants' demographics or psychiatric/neurological states; (2) Regarding the Intervention, studies were considered if they included a validated measure of previous alcohol exposure (i.e., lifetime/recent alcohol consumption); (3) Regarding the Comparator, studies were considered if they offered a direct comparison between an experimental group confronted with alcohol exposure and a matched control group, a main analysis including alcohol-related measures (e.g., a correlational analysis exploring the influence of alcohol consumption on dependent variables), or an experimental condition presenting alcohol-related stimuli and a matched control condition presenting non-alcohol-related stimuli; (4) Regarding the Outcome, studies were included if they proposed at least one eye tracking index as a dependent variable (i.e., pupillary diameter, initial fixation, number/time of saccades, eye movements, gaze direction, dwell time); (5) Regarding the Setting, studies proposing comparisons between groups or experimental conditions (i.e., interventional, observational, cross-sectional) were considered, thus excluding single-case or case series studies and studies without experimental data.

We followed the guidelines of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) and the related 27-item checklist (Moher et al., 2009). We focused on peer-reviewed articles published in English, between the 1st of January 2000 and the 1st of July 2019 and included in at least one of the three following databases: PsycINFO, Pubmed and Scopus. We aimed to include every study using eye tracking indexes in relation to alcohol consumption, without limits related to participants' demographics or condition (e.g., neurological or psychopathological states), sample size, or processes/variables explored. As we wanted to focus on peer-reviewed papers, the grey literature (e.g., conference proceedings, unpublished PhD dissertations) was not considered, but we included papers in press and papers presenting null findings. The search phrase (marginally tailored to match the specificities of each database) combined eye tracking (i.e., "eye tracking" OR "eye-tracking" OR "eye movements" OR "visual tracking" OR "gaze tracking") and alcohol (i.e., "alcoholism" OR "alcohol dependence" OR "alcohol use disorder" OR "binge drink*" OR "heavy drink*" OR "social drink*" OR "episodic drink*" OR "college drink*" OR "alcohol*") terms. The initial search led to identifying 1084 papers (327 in PsycINFO, 247 in Pubmed, 510 in Scopus). The selection of the papers included was then conducted through a 3-step procedure (Fig. 1): First, duplicates were removed, leading to the identification of 733 unique papers. Second, titles and abstracts were screened to remove papers presenting one of the following exclusion criteria: (1) No eye tracking measure (261 papers excluded); (2) No addictive substance-related measure (268 papers excluded); (3) No human sample (i.e., animal studies; 32 papers excluded); (4) No experimental data presented (i.e., review, meta-analysis, reply, commentary, erratum, conference proceedings; 68 papers excluded). 629 papers were excluded using this procedure. If this initial screening did not allow to determine the presence of an exclusion criterion, the paper was included in the full-text reading phase. Third, the 104 remaining papers were screened through full-text reading. Sixty-eight papers were excluded during this phase because they (1) only considered alcohol consumption measures as control variables, were centrally focused on other substance abuse or did not report alcohol-related results (31 papers excluded); or (2) did not include participants with diagnosed sub-clinical or clinical AUD, or with a validly evaluated and clearly labeled excessive alcohol consumption pattern, or did not propose a valid measure of alcohol consumption habits (37 papers excluded). Among these studies, several ones evaluated alcohol consumption through validated questionnaires but were excluded because they did not report alcohol consumption scores (e.g., Brown and Richardson, 2012; Thomsen and Fulton, 2007; Vincke and Vyncke, 2017) or did not consider the influence of alcohol-related measures on eye tracking indexes (e.g., Friese et al., 2010; Frings et al., 2018; Jędras et al., 2018; Moss et al., 2015; Qureshi et al., 2018; Rose et al., 2013, 2018; Sillero-Rejon et al., 2019; Wilcockson and Pothos, 2016; Yzer et al., 2017). This procedure ended up in the selection of 36 papers, which were included in the systematic review. It should be noted that several papers (Childs et al., 2012; Fernie et al., 2012; King and Byars, 2004; Miller and Fillmore, 2011; Roberts et al., 2014; Roche and King, 2010; Roche et al., 2014; Schoenmakers et al., 2008; Weafer and Fillmore, 2013) simultaneously explored alcohol intoxication and global drinking pattern by exploring the modification of eye movements following alcohol intoxication among people presenting high levels of alcohol consumption. These papers were mostly offering insights on the effects of alcohol intoxication, and most of them did not offer a comprehensive evaluation of the alcohol consumption pattern presented by participants, but they have nevertheless been included and their results related to the alcohol consumption pattern have been described. This identification and selection procedure has been initially performed by the first author and then cross-checked by the last one, who performed the search independently, using the same criteria. Discussions between the first and last authors resolved discrepancies in the selection of the articles. Discussions with all the authors resolved the remaining disagreements.

Methodological Quality Assessment

As underlined in papers reviewing methodological quality assessment scales (Sanderson et al., 2007; Zeng et al., 2015), there is currently no gold-standard tool for assessing cross-sectional studies. The "Strengthening The Reporting of Observational studies in Epidemiology" (STROBE) statement (von Elm et al., 2007) has been widely used in previous systematic reviews (e.g., Bosaipo et al., 2017), but this procedure has been criticized (Da Costa et al., 2011): the STROBE is a tool designed to guide authors when reporting observational studies, and it should thus not be used to propose a post-hoc assessment regarding the methodological quality of studies included in systematic reviews or meta-analyses. We have decided to evaluate the methodological quality of each reviewed study using an adapted version of the "quality assessment tool for observational cohort and cross-sectional studies", developed by the

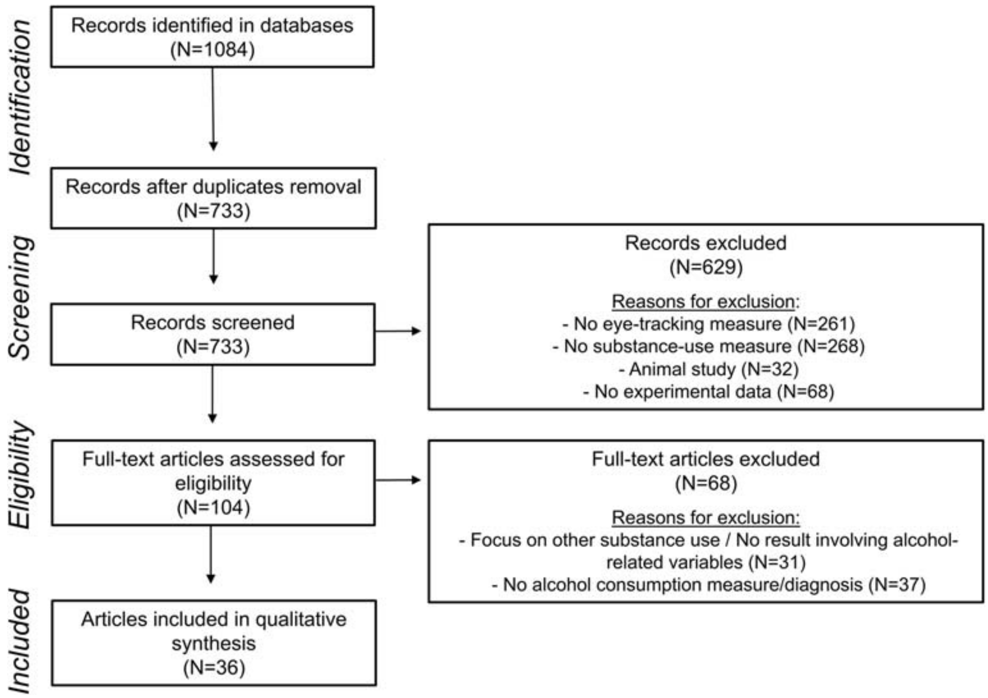

Fig. 1 PRISMA flow diagram presenting the selection (identification, screening, eligibility, inclusion) of the papers reviewed

National Heart, Lung and Blood Institute (NHLBI, 2014). This scale appears as the most adapted for our purpose, as most studies included in the present paper are cross-sectional and as it has been recently used in systematic reviews on similar topics (e.g., Carbia et al., 2018). However, several adaptations have been conducted to cope with the specific needs of the present paper: (1) two items of the original scale have been removed from the evaluation as they were not adapted to the studies included (i.e., item 3: "Was the participation rate of eligible persons at least 50%?"; item 13: "Was loss to follow-up after baseline 20% or less?"); (2) as several key items related to participants' selection (item 4), statistical analyses (item 5), exposure measures (item 9), outcome measures (item 11) and confounding variables (item 14) included several sub-questions, they have been split into separated items. The assessment scale used here thus comprised 20 items with a binary answer (Yes/No), leading to a raw rating between 0 and 20. For each study, a score (i.e., percentage of items with a "Yes" answer) was computed, leading to a global quality rating (i.e., poor for scores below 50%, fair for scores between 50 and 69%, good for scores between 70% and 79%, strong for scores of 80% and beyond, adapted from Black et al., 2017), reported in Table 1. The Supplementary Table 1 presents the detailed score obtained for each study on each item. It should be noted that, as our methodological quality assessment was based on the information reported in each paper, it can be considered as partly evaluating methodological quality reporting rather than methodological quality per se. Indeed, some criteria considered as unfulfilled in our assessment might have been considered but unreported in the study.

Data Extraction and Synthesis

A systematic data extraction procedure determined, for each paper, the characteristics regarding five categories of variables (adapted from the PICOS procedure): (1) Participants (sample size, age, gender ratio, exclusion criteria); (2) Exposures (psychiatric/neurological diagnosis or (sub-)clinical classification, alcohol-consumption measure, psychopathological comorbidities); (3) Comparator (control group presence and size, matching variables); (4) Design (processes measured, tasks, stimuli, eye tracking indexes, eye tracking materials); (5) Outcomes (main results, limitations, key conclusions, methodological quality). A comprehensive synthesis of the data is presented in Table 1. For the sake of clarity and despite the presence of overlap across processes in some studies, the presentation of the results is organized in sections, each focusing on one type of cognitive process, in line with the classic neuropsychological categories used in literature reviews describing the correlates of alcohol-related disorders (Carbia et al., 2018; Oscar-Berman et al., 2004; Stavro et al., 2013). We successively present the work focusing on perceptive abilities, attentional bias, and higher cognitive abilities (executive functions and decision making). A specific section is dedicated to studies focusing on emotional processes, and the last one presents studies that used eye tracking as a tool to clarify the efficiency of interventions aiming at reducing alcohol consumption. After a brief overview of the general characteristics presented by the selected studies, the main results related to quality assessment are described, before reviewing the key outcomes obtained concerning each key process.

Table 1 Description and main results of eye tracking studies on alcohol-related disorders

Authors (year)	Population				Exposures	
	Sample (N)	*Age [M(sd)]*	*Gender ratio (% males)*	*Exclusion criteria*	*Diagnosis / Characteristics*	*Alcohol measure*
Ceballos et al. (2009)	26	20.6 (2.0)	85%	Poor quality of eye tracking data	Non-drinkers/regular drinkers	QFI
Childs et al. (2012)	13	26.9 (1.1)	53%	Substance dependence Serious medical condition >5 cigarettes/day High blood pressure Abnormal EEG BMI <19 or > 26 Age < 21 or > 45 Pregnancy/Lactation Alcohol/drug consumption 24 h before testing	Heavy social drinkers (>9 doses/week) >0 binge episode/week [>4 (men) or > 3 (women) doses on one occasion]	Adapted SCID Drinking days/month Doses/drinking day Binge episodes in last 30 days
Choi and Lee (2015)	40	NR	NR	Scores beyond 2 SD above the mean for craving measures	Heavy social drinkers [AUDIT >11] Light drinkers [AUDIT <8]	AUDIT AUQ
Christiansen et al. (2015a)	60	20.0 (2.0)	35%	Alcohol dependence Visual impairment	Heavy drinkers	TLFB AUDIT Doses/week Desire for alcohol
Claisse et al. (2016)	23 (short-term absti-nence) 26 (long-term absti-nence)	44.4 (7.5) 49.0 (7.6)	82% 61%	Age < 18 or > 60	Severe alcohol-use disorder (DSM-5)	Age at first contact / dependence Familial history of alcohol-related problems Doses/day Previous treatments Alcohol craving
Fernie et al. (2012)	52	21.2 (2.8)	49%	Alcohol dependence Drugs interacting with alcohol consumption Age < 18 or > 30 No drinking occasion (>5 drinks) in the last 14 days Pregnancy	Heavy drinkers [>21 (men) or > 14 (women) doses/week] Moderate drinkers [<22 (men) or < 15 (women) doses/week]	TLFB AUDIT AAAQ Desires for Alcohol Subjective intoxication scale
Field et al. (2011)	54	19.9 (1.5)	53%	Non drinker Visual impairment	Light / heavy drinkers	TLFB AUDIT AAAQ Doses/week
Harris et al. (2009)	85	22.9 (6.5)	0%	NR	Non-drinkers/regular/heavy drinkers	Number of doses in the last day / last week / typical week
Hobson et al. (2013)	58	24.5 (7)	41%		Regular drinkers	TLFB

Table 1 (continued)

				Absence of recent alcohol consumption		Desires for Alcohol Severity of alcohol dependence
Iacono et al. (2000)	119	17.2 (0.4)	100%	NR	NR	DSM-III-R criteria for alcohol dependence Substance Abuse Lifetime intoxications number Last year consumption Maximum consumption per day
Jones and Field (2013)	60	21.2 (3.0)	47%	Alcohol-related disorders	Heavy social drinking [>21 doses/week (men), >14 doses/week (women)]	TLFB AUDIT AAAQ Doses/week
Jones et al. (2012)	29	21.2 (3.3)	45%	Alcohol-related disorders	Regular drinkers	TLFB AUDIT Doses/week
Kersbergen and Field (2017)	Study 1: 60 Study 2: 120	Study 1: 21.3 (3.6) Study 2: 24.2 (8.2)	37% 35%	Age < 18 Wearing glasses	Study 1: Regular alcohol consumers Study 2: Heavy drinkers [>21 (men) or > 14 (women) doses/week]	AUDIT TLFB (14 last days)
King and Byars (2004)	34	28.6 (0.7)	76%	Substance dependence Current/past psychiatric or medical disorder Pregnancy	Heavy drinkers (>9 doses/week) >0 binge episode/week [>4 (men) or > 3 (women) doses on one occasion] Low social drinkers doses/week)	B-MAST Drinking days/week Doses/drinking day Binge episodes in last 180 days
Laude and Fillmore (2015)	24	24.1 (3.2)	50%	Alcohol use disorder Psychiatric disorder Non regular drinker	Social drinkers	TLFB B-MAST
Lee et al. (2014)	41	21.3 (2.6)	49%	NR	Hazardous drinkers (AUDIT>8)	AUDIT AAAQ Consumption frequency/intensity
Lee and Lee (2015)	43	22.0 (2.5)	40%	NR	Problematic drinkers (AUDIT>8)	AUDIT AAAQ Consumption frequency/quantity Readiness to change questionnaire
Marks et al. (2015)	40	43.4 (7.5)	70%	Psychotropic medication Withdrawal symptoms	Cocaine dependence	AUDIT B-MAST SCID Doses, doses/episode, drinking episodes in last 30 days
McAteer et al. (2015)	44	17.1	66%	NR	Non-drinkers (AUDIT = 0) Light drinkers (AUDIT<9) Heavy drinkers (AUDIT>8)	AUDIT Alcohol expectancies Age at first drink Abstinence duration
McAteer et al. (2018)	139		46%	Psychological	Non-drinkers (AUDIT = 0),	AUDIT

Table 1 (continued)

		Early adolescents: 12.63 Late adolescents: 17.1 Young adults: 20.19		/ neurological disorder Visual impairment	Light drinkers (AUDIT<9) Heavy drinkers (AUDIT>8)	
Miller and Fillmore (2010)	25	24.0 (3.8)	56%	Alcohol dependence Recent drug use	Regular drinkers	TLFB B-MAST
Miller and Fillmore (2011)	20	22.8 (2.6)	65%	Alcohol dependence Recent drug use	Frequent drinkers (>1 drinking occasion/month, >1 dose/occasion)	B-MAST
Monem and Fillmore (2017)	35	24.6 (3.4)	46%	Alcohol dependence Visual impairment	Regular drinkers	TLFB AUDIT
Monk et al. (2017a)	22	21.3 (1.7)	32%	NR	Heavy drinkers	AUDIT Alcohol expectancies
Qureshi et al. (2019)	41	21.5 (6.6)	22%	Non drinkers (AUDIT = 0)	Regular drinkers	AUDIT
Roberts et al. (2014)	80	23.3 (2.4)	41%	Alcohol dependence Psychiatric disorder Age < 21 or > 35 Drug consumption Pregnancy	Regular/Social drinkers	TLFB B-MAST (Binge) Drinking days and number of doses in last 90 days
Roche and King (2010)	138	25.6 (0.6)	57%	Substance dependence Current/past psychiatric or medical disorder Pregnancy	Heavy drinkers (>9 doses/week) >0 binge episode/week [>4 (men) or > 3 (women) doses on one occasion] Low social drinkers (<6 doses/week)	B-MAST Drinking days/week Doses/drinking day Binge episodes/month
Roche et al. (2014)	104	24.9 (0.2)	62.5%	Substance dependence Current/past psychiatric or medical disorder Pregnancy BMI <19 or > 30 Age < 21 or > 29	Heavy drinkers (>9 and < 41 doses/week) >0 binge episode/week [>4 (men) or > 3 (women) doses on one occasion]	TLFB Quantity-Frequency Interview Drinking days /month Doses/drinking day Binge episodes /month Maximum doses/occasion
Roy-Charland et al. (2017)	Study 1: 78 Study 2: 76	Study 1: 22.9 (6.4) Study 2: 20.6 (4.9)	76% 88%	NR	NR	Khavari Alcohol Test Annual absolute intake
Schoenmakers et al. (2008)	22	20.3 (2.2)	55%	NR	Heavy drinkers [>21 (men) or > 14 (women) doses/week]	TLFB AUDIT Desires for Alcohol Subjective intoxication scales
Sillero-Rejon et al. (2018)	128	22 (4)	50%	Age < 18 Absence of recent alcohol consumption	Heavy drinking (>14 doses) during the last week	AUDIT Doses/day in the last week
van Duijvenbode et al. (2012)	30	39.6 (12.2)	82%	Visual impairment	Abstinent drinkers with intellectual disabilities	AUDIT Abstinence duration Substance (mis)use in intellectual disability questionnaire Alcohol craving

Table 1 (continued)

van Duijvenbode, et al. (2017)	94	42.5 (11.6)	29.3%	NR	Light / heavy drinkers	AUDIT Substance (mis)use in intellectual disability questionnaire Alcohol craving
Weafer and Fillmore (2013)	40	23.4 (2.6)	55%	Substance use disorder Neurological/medical disorder	Heavy drinkers (>9 doses/week) >0 binge episode/week [>4 (men) or > 3 (women) doses on one occasion] Low social drinkers (<5 doses/week)	TLFB B-MAST Desire for alcohol Doses/occasion Binge/drunk episodes in last 90 days Drinking occasions / doses in last 90 days
Wilcockson and Pothos (2015)	86	20.9 (4.5)	36%	NR	NR	Doses/week
Wilcockson et al. (2019)	19	22.2 (4.6)	36.84%	NR	Heavy drinkers	Doses/week Desire for Alcohol Alcohol outcome expectancy

Authors (year)	Exposures	Comparator		Design		
	Comorbidities	*Control group*	*Matching variables*	*Processes measured*	*Tasks*	*Stimuli*
Ceballos et al. (2009)	NR	None (correlational analyses)	None	Attentional bias towards alcohol-related cues	Free visual exploration	20 alcohol-images 20 matched neutral images
Childs et al. (2012)	Nicotine dependence Other drug use	None (within-subject design): Alcohol intoxication Sobriety	None	Automatic (prosaccade) and controlled (antisaccade, pursuit) eye movements	Saccade task Smooth pursuit task	Still (saccade task) or moving (smooth pursuit) targets
Choi and Lee (2015)	NR	20 heavy social drinkers 20 light drinkers	NR	Attentional bias towards alcohol-related cues	Visual probe task	Alcohol-related scenes Neutral scenes
Christiansen et al. (2015a)	NR	None (within-subject design)	NR	Attentional bias towards alcohol-related cues	Visual probe task	64 alcohol-images 64 matched neutral images
Claisse et al. (2016)	Depression Anxiety Cognitive level Emotional competences	28 matched healthy controls	NR	Emotional reactivity	Valence/intensity judgments on emotional scenes	20 positive scenes 20 negative scenes 20 neutral scenes
Fernie et al. (2012)	NR	26 heavy drinkers 26 moderate drinkers	Age Gender	Attentional bias towards alcohol-related cues	Visual probe task	10 alcoholic beverage images 10 matched objects images
Field et al. (2011)	NR	NR	NR	Attentional bias towards alcohol-related cues	Free visual exploration	10 alcohol-related images 10 matched control images
Harris et al. (2009)	NR	Between-subject design: 43 in negative condition (low credibility cues) 42 in positive condition (high credibility cues)	NR	Attention to alcohol-related health messages	Free visual exploration	Web pages presenting health message together with low (adverts) or high (trustmark) credibility cues
Hobson et al. (2013)	NR	Light / heavy drinkers with low / high craving	Age	Attentional bias towards alcohol-related cues	Flicker paradigm	16 complex real world scenes

Table 1 (continued)

							4X4 objects grids with alcohol-related / neutral images
Iacono et al. (2000)		Nicotine dependence Illicit drug dependence	High / Medium /Low risk of substance dependence	NR	Controlled (antisaccade) eye movements	Saccade task	Black dots
Jones and Field (2013)		Impulsivity Mood introspection	Between-subject design: 30 in alcohol-condition 30 in control condition	Age Gender Impulsivity Mood	Automatic (prosaccade) and controlled (antisaccade) eye movements	Saccade task with alcohol/neutral cues	Alcohol-related images Neutral images
Jones et al. (2012)		NR	NR	NR	Attentional bias towards alcohol-related cues	Free visual exploration	10 alcohol-related images 10 chocolate-related images 10 matched control images
	Kersbergen and Field (2017)	NR	Study 1: None Study 2: Betwee-subject design 60 in alcohol advice condition 60 in control condition	Age Gender AUDIT TLFB	Attention to alcohol-related health/warning messages	Free visual exploration followed by memory task	40 beverage containers of alcoholic (20- and non-alcoholic (20) beverages including health /warning labels
King and Byars (2004)		Personality, affective, sensation seeking measures	20 heavy drinkers 14 light drinkers	Age Gender Personality, affective, sensation seeking measures	Automatic (prosaccade) and controlled (smooth pursuit) eye movements	Saccade task Smooth pursuit task	Still (saccade task) or moving (smooth pursuit) white dots
Laude and Fillmore (2015)		Impulsivity	Between-subject design: 12 in alcohol-condition 12 in control condition	Gender	Influence of alcohol-related stimuli on conditioned inhibition learning Attentional bias towards alcohol-related cues	Conditioned inhibition task Visual probe task	one alcoholic beverage image one soft drink image
Lee et al. (2014)		Anxiety	Individuals with/without ambivalence towards alcohol	Age Gender AUDIT Anxiety	Attentional bias towards alcohol-related cues	Free visual exploration	20 alcohol-related images 20 matched neutral images
Lee and Lee (2015)		Anxiety	Between-subject design: 22 in psychoeducation condition 21 in attentional bias modification condition	Age Gender Alcohol consumption Anxiety	Attentional bias towards alcohol-related cues	Free visual exploration Visual probe task with contingency	20 alcohol-related images 20 matched neutral images
Marks et al. (2015)		Global mental status	Alcohol-dependence No alcohol dependence	Age Gender Ethnical group Mental status Education Nicotine dependence	Attentional bias towards alcohol-related cues	Visual probe task	5 cocaine-related images 5 alcohol-related images 5 matched neutral pictures
McAteer et al. (2015)		NR	Non / light / heavy drinkers	Age	Attentional bias towards alcohol-related cues	Free visual exploration	60 alcohol-related images 60 matched neutral images
McAteer et al. (2018)		NR		NR			60 alcohol-related images

Table 1 (continued)

		Non / light / heavy drinkers of various ages		Attentional bias towards alcohol-related cues	Free visual exploration	60 matched neutral images
Miller and Fillmore (2010)	NR	NR	NR	Attentional bias towards alcohol-related cues	Visual probe task	20 alcohol-related images 20 matched neutral images
Miller and Fillmore (2011)	NR	None (within-subject design)	None	Attentional bias towards alcohol-related cues Saccadic efficiency	Visual probe task	10 alcoholic beverage images 10 matched soft drink images
Monem and Fillmore (2017)	NR	None (correlational analyses)	NR	Attentional bias towards alcohol-related cues	Free visual exploration	Recreational room with 4 alcohol-drinks and 4 matched soft-drinks
Monk et al. (2017a)	NR	Between-subject design: 11 in arousal condition 11 in neutral condition	Age Gender AUDIT	Attention to alcohol warning messages	Free visual exploration	50 alcohol prevention messages (text/image)
Qureshi et al. (2019)	NR	Median-split on AUDIT: 23 non-problem drinkers 18 problem drinkers	Gender	Attentional bias towards alcohol-related cues Saccade inhibition	Gaze contingency paradigm	30 non-alcoholic appetitive 30 alcoholic appetitive images 30 matched non-appetitive images
Roberts et al. (2014)	NR	None (within-subject design)	None	Inhibitory saccadic control Saccadic latency/accuracy	Delayed ocular response task	White circles
Roche and King (2010)	SCID	78 heavy drinkers 60 light drinkers	Age Gender BMI	Automatic (prosaccade) and controlled (antisaccade, pursuit) eye movements	Saccade task Smooth pursuit task	Still (saccade task) or moving (smooth pursuit) targets
Roche et al. (2014)	SCID	104 heavy drinkers from a previous cohort	Age Gender Education BMI Familial history of alcoholism	Automatic (prosaccade) and controlled (antisaccade, smooth pursuit) eye movements	Saccade task Smooth pursuit task	Still (saccade task) or moving (smooth pursuit) targets
Roy-Charland et al. (2017)	NR	None (correlational analyses)	NR	Attentional bias towards alcohol-related cues	Free visual exploration Memorization task	54 (Study 1) / 88 (Study 2) complex visual scenes, half containing alcohol-related stimuli
Schoenmakers et al. (2008)	NR	None (within-subject design)	None	Attentional bias towards alcohol-related cues	Visual probe task	14 alcohol-related scenes 14 matched non-alcohol related scenes
Sillero-Rejon et al. (2018)	NR	Between-subject design: 64 in self-affirmation condition 64 in control condition	Gender	Attention to alcohol warning pictures	Free visual exploration	6 moderate health warning images 6 explicit health warning images
van Duijvenbode et al. (2012)	IQ	Light / moderate / heavy drinkers with mild / borderline / average intellectual disabilities	Age Gender Abstinence duration	Attentional bias towards alcohol-related cues	Visual probe task	48 alcohol-related images 52 matched soft drinks images
van Duijvenbode, et al. (2017)	IQ Psychiatric comorbidi-ties	Light / heavy drinkers with or without intellectual disabilities	Age Craving	Attentional bias towards alcohol-related cues	Visual probe task	48 alcohol-related images 52 matched soft drinks images
Weafer and Fillmore (2013)	NR	20 heavy drinkers 20 light drinkers	Gender BMI	Attentional bias towards alcohol-related cues	Visual probe task	10 alcoholic beverage images 10 matched soft drink images
Wilcockson and Pothos (2015)	NR	None (correlational analyses)	NR	Attentional bias towards alcohol-related cues	Gaze contingency paradigm	16 alcohol-related images 16 matched neutral images

Table 1 (continued)

Wilcockson et al. (2019)	NR	None (within-subject design)	NR	Saccade inhibition Attentional bias towards alcohol-related cues	Free visual exploration	18 alcohol-related images 18 matched neutral images

Authors (year)	**Design**		**Outcomes**			
	Eye tracking indexes	*Eye tracking materials / Sampling rate*	*Main results*	*Limits*	*Key conclusions*	*Methodological quality*
Ceballos et al. (2009)	Initial fixation Dwell time Pupillary diameter	Tobii ×120 (Tobii Technology) Head-free infrared camera 120 Hz	Positive correlation between quantity-frequency index of alcohol consumption and initial fixation / dwell time on alcohol-related stimuli No correlation between quantity-frequency index of alcohol consumption and pupil diameter during fixation of alcohol-related stimuli	No control on comorbidities/-biasing variables Limited evaluation of chronic consumption	The intensity of alcohol consumption is correlated with the automatic (initial fixation) and controlled (dwell time) correlates of alcohol-related bias.	Fair
Childs et al. (2012)	Gain (participant's eye velocity compared to target's velocity) Saccadic latency, velocity, accuracy	VisualEyes VNG System (Micromedical Technologies) Head-mounted monocular camera	Impaired gain and higher saccadic latency during high intoxication in heavy drinkers Deficits partly compensated by varenicline	Limited sample size Single dose of varenicline	Varenicline (2 mg) reduces the eye movements deficits induced by high intoxication (0.8 g/kg) in heavy drinkers	Fair
Choi and Lee (2015)	Dwell time	iView XTM RED-III (SensoMotoric Instruments)	Reduced dwell time towards alcohol-related stimuli following virtual covert sensitization No difference between light and heavy drinkers regarding dwell time reduction	Limited validity of the eye tracking measure Weak control on comorbidities/-biasing variables	Virtual covert sensitization reduces the attentional bias at short term	Fair
Christiansen et al. (2015a)	Dwell time	Eye-Trac D6 (Applied Science Laboratories) 120 Hz	Increased internal reliability of the visual probe task when using dwell time (compared to reaction time) and personalized stimuli Increased intensity of attentional bias at behavioral level for personalized stimuli No correlation between attentional bias and alcohol consumption or craving	Limited use of eye tracking measure Weak control on comorbidities/-biasing variables Unclear definition of hazardous drinking	Eye tracking measure and personalized stimuli increase the internal reliability of the visual probe task, but attentional bias is not correlated with consumption/craving (indexing poor construct validity)	Fair
Claisse et al. (2016)	Pupillary diameter	RED-M (SensoMotoric Instruments)	Intensified pupillary reactivity for positive/negative scenes in patients with short-term abstinence	Low group matching No control on biasing variables	Severe alcohol-use disorders are associated with increased pupillary reactivity towards emotional and neutral scenes,	Fair

Table 1 (continued)

			Head-free infrared camera 120 Hz	Intensified pupillary reactivity, independent of stimulus' emotional valence for all patients Negative correlation between pupillary reactivity and abstinence duration		which decreases with abstinence	
Fernie et al. (2012)		Dwell time	Eyetrace 300x (Applied Science Laboratories) Head-mounted infrared camera	No behavioral attentional bias in moderate/heavy drinkers Higher dwell time towards alcohol-related cues in heavy drinkers, independently of intoxication level	Alcohol consumption measure focused on two last weeks Weak distinction between light and heavy drinkers No control of biasing variables	Attentional bias (higher dwell time for alcohol-related stimuli, without difference at behavioral level) in heavy drinkers Attentional bias not modified by acute alcohol consumption	Fair
Field et al. (2011)		Dwell time	Eyetrace 300x (Applied Science Laboratories)	Attentional bias in heavy drinkers (higher dwell time), independently of alcohol expectancy Attentional bias in light drinkers (higher dwell time), only when alcohol expectancy is high	Limited use of eye tracking measure Weak control on comorbidities/-biasing variables Unclear definition of light/heavy drinking	Heavy drinking is associated with a stable attentional bias, which is only present when alcohol expectancies are high among light drinkers	Fair
	Harris et al. (2009)	Dwell time	iViewX (SensoMotoric Instruments)	No influence of cues credibility on the dwell time for health message Higher dwell time on content-irrelevant parts of the website for low credibility cues Stronger impact of health message on alcohol consumption for high credibility cues, particularly among women with heavy alcohol consumption	Limited evaluation of chronic consumption Limited use of eye tracking measure Weak control on comorbidities/-biasing variables	Content-irrelevant cues modulates the influence of health-risk information on alcohol consumption, particularly among heavy drinkers	Fair
Hobson et al. (2013)		Latency/orientation of first saccade Number of fixations Dwell time	EyeLink II (SR Research) Head-mounted infrared camera 500 Hz	No attentional bias on eye tracking measure in heavy drinkers Higher alcohol-related changes detection in real world scenes among heavy drinkers Higher alcohol-related changes detection and faster saccade towards alcohol images in real scenes among individuals with high craving	No control on biasing variables Median split on consumption and craving Incoherent pattern of behavioral/eye tracking results at the flicker task	No global attentional bias is observed in a flicker task, but heavy drinkers and individuals with high craving present higher alcohol-related changes detection in real world scenes, and high craving is associated with faster initial saccade towards alcohol	Fair
Iacono et al. (2000)		Percentage of correct saccades	Electrooculogram Electrodes placed above pupil	Correlation between impaired electrodermal regulation /	Low number of items at the antisaccade task	Adolescents at high risk for substance use (indexed by impaired electrodermal	Fair

Table 1 (continued)

			and near the outer canthus of one eye 256 Hz	reduced P3 amplitude and risk for substance dependence Correlation between reduced antisaccade performance and impaired electrodermal response, but not P300 deficit	No report of eye tracking measure Unability to distinguish the influence of pre-consumption vulnerability and personal consumption	regulation) have reduced performance at the antisaccade task	
Jones and Field (2013)		Percentage of correct saccades Correct saccade latency	Eye-Trac D6 (Applied Science Laboratories) Head-free infrared camera 120 Hz	Reduced behavioral outcome (i.e. immediate post-training alcohol consumption) when using alcohol-related cues during motor inhibition training No change in behavioral outcome when using alcohol-related cues during oculomotor inhibition training Increased prosaccade latency towards alcohol cues in oculomotor inhibition training with alcohol-related cues	Limited use of eye tracking measure Limited evaluation of chronic consumption Weak control on comorbidities/-biasing variables	The use of alcohol-related stimuli (instead of neutral one) does not strongly influence the impact of motor/oculomotor inhibition training on consumption	Fair
Jones et al. (2012)		Dwell time	Eye-Trac D6 (Applied Science Laboratories) Head-free infrared camera 120 Hz	Increased attentional bias in social drinkers (higher dwell time) when reward expectancy is high, independently of the expected reward (present for alcohol and chocolate rewards)	Limited use of eye tracking measure Weak control on comorbidities/-biasing variables Unclear definition of social drinking	Reward expectancy increases attentional bias, this effect being independent of the expected reward (alcohol/chocolate)	Fair
	Kersbergen and Field (2017)	Dwell time	ASL Eye-Trac D6 (Applied Science Laboratories) 120 Hz	Low dwell time on alcohol-related health/warning messages Negative correlation between dwell time and motivation to reduce drinking No modification of dwell time following an intervention reducing drinking motivation No modification of dwell time following increased visual salience of warning label	Low control on chronic consumption Limited use of eye tracking measure Weak control on comorbidities/-biasing variables	Alcohol drinkers pay limited attention to health/warning messages presented on alcohol packaging. This attention is not modulated by interventions reducing drinking motivation, nor by increased salience of health/warning messages	Fair
King and Byars (2004)		Saccadic latency and velocity (saccade task) Time on target (smooth pursuit)	Eye-Trac 210 (Applied Science Laboratories) Head-mounted infrared camera 500 Hz	Reduced time on target and saccadic velocity but increased saccadic latency during high intoxication in low drinkers and heavy drinkers Low influence of chronic consumption on eye	Small sample Mostly male participants	Chronic alcohol consumption does not modulate the smooth pursuit and saccadic latency/velocity modifications related to high alcohol intoxication	Fair

Table 1 (continued)

			movements' impairments generated by acute alcohol consumption			
Laude and Fillmore (2015)	Dwell time	Tobii T120 (Tobii Technology) Head-free infrared camera 120 Hz	Attentional bias in frequent drinkers Reduced conditioned inhibition when learning conducted with alcohol-related cues (compared to soft cues)	Limited use of eye tracking measures Low control on chronic consumption	Alcohol-related cues, by hijacking attentional resources, reduce conditioned inhibition learning in frequent drinkers	Fair
Lee et al. (2014)	Latency/duration of first fixation Number of fixations Dwell time	iView XTM Red-IV (SensoMotoric Instruments) Head-free infrared camera 60 Hz	Automatic part of attentional bias (shorter latency and longer duration of initial fixation) among all hazardous drinkers Controlled part of bias (increased total dwell time and total number of fixations) only among drinkers without alcohol ambivalence	Disputable implementation of ambivalence measure Low control on chronic consumption	Hazardous drinkers have an automatic attentional bias (initial fixation latency/duration), but the bias related to controlled processes (dwell time, number of fixations) is only present among individuals without alcohol ambivalence	Fair
Lee and Lee (2015)	Dwell time	iView XTM Red-IV (SensoMotoric Instruments) Head-free infrared camera 60 Hz	Reduced attentional bias (dwell time) after attentional training in problematic drinkers Change related to increased control on alcohol avoidance, without modification of automatic approach tendencies No change in explicit alcohol ambivalence after attentional training	Limited use of eye tracking measures Low control on chronic consumption Unclear automatic/ controlled processes distinction	Attentional bias is reduced following bias modification training in problematic drinkers, this change being centrally related to an increase in controlled alcohol avoidance	Fair
Marks et al. (2015)	Dwell time	Tobii T60-XL / Tobii X2/60 (Tobii Technology) Head-free infrared camera 60 Hz	No behavioral attentional bias in alcohol-dependent individuals with comorbid cocaine dependence Attentional bias for eye tracking measures (higher dwell time) Attentional bias specific to the substance used (cocaine and/or alcohol)	No group with alcohol use disorders only Heterogeneous population Weak control on comorbidities/- biasing variables	Attentional bias is indexed by eye tracking (but not behavioral) measures in alcohol-dependent individuals with comorbid cocaine dependence, but absent in cocaine-dependent individuals without alcohol-use disorders	Fair
McAteer et al. (2015)	Latency/orientation of first fixation Dwell time	Red Eye Tracker (SensoMotoric Instruments) Head-free infrared camera 250 Hz	No attentional bias in adolescents, whatever the consumption Higher dwell time for alcohol stimuli among heavy drinkers for controlled processes (i.e. late viewing period) No group difference on automatic processes (i.e.	Heterogeneous population and stimuli Limited evaluation of chronic consumption Weak control on comorbidities/- biasing variables	Adolescent heavy drinkers do not present attentional bias but have increased controlled attention towards alcohol-related stimuli (late viewing dwell time) when compared to non/light drinkers	Fair

Table 1 (continued)

			initial fixation, dwell time during early viewing period)			
McAteer et al. (2018)	Orientation of two first fixations Dwell time	Red Eye Tracker (SensoMotoric Instruments) Head-free infrared camera 250 Hz	No attentional bias in adolescents or young adults, whatever the consumption Higher dwell time for alcohol stimuli among heavy drinkers, independently of age Increased percentage of initial fixation towards alcohol in young adults, independently of consumption	Mixing between age-related and alcohol-related influence on bias Limited evaluation of chronic consumption Weak control on comorbidities/-biasing variables	Young heavy drinkers do not present attentional bias, but dwell time towards alcohol stimuli is increased in heavy drinking, and the percentage of initial fixations towards these stimuli increases with age	Fair
Miller and Fillmore (2010)	Dwell time	504 Eye Tracker (Applied Science Laboratory) Head-free infrared camera 60 Hz	Attentional bias among regular drinkers when confronted with isolated alcohol images Correlation between bias and intensity/frequency of consumption No bias for complex stimuli (i.e. scenes) Higher efficiency for eye tracking (dwell time) than behavioral measures (reaction times)	Limited use of eye tracking indexes No focus on heavy drinking No control group	Regular drinkers present an attentional bias when confronted with simple (but not complex) alcohol pictures, and dwell time is a better index than behavioral measures	Fair
Miller and Fillmore (2011)	Saccadic accuracy and velocity Dwell time	504 Eye Tracker (Applied Science Laboratory) Head-free infrared camera	No behavioral attentional bias in heavy drinkers, independent of acute alcohol consumption Higher dwell time towards alcohol-related cues among heavy drinkers, independent of acute alcohol consumption	No control group Small sample No control of biasing variables	The attentional bias (higher dwell time for alcohol-related stimuli, without difference at behavioral level) in heavy drinkers is not modified by alcohol intoxication	Fair
Monem and Fillmore (2017)	Dwell time	Tobii Pro Glasses 2 (Tobii Technology) Head-mounted infrared camera 60 Hz	No attentional bias during the first in vivo visual exploration of real life environment Attentional bias during the second visual exploration (i.e. reduced dwell time due to habituation for soft images, not for alcohol) Correlation between attentional bias and consumption intensity (but not frequency)	Limited use of eye tracking measures No control of biasing variables Low control on chronic consumption	Regular drinkers present a bias for controlled (but not automatic) attentional processes, this bias being correlated with consumption intensity	Fair
Monk et al. (2017a)	Dwell time	EyeLink II (SR Research) Head-mounted infrared camera 500 Hz	Higher dwell time for image than text, independently of its explicit nature Correlation between dwell time and post-study increase of positive alcohol expectancies	Limited use of eye tracking measure No control of biasing variables Low control on chronic consumption	Heavy drinkers focus their attentional resources on visual rather than textual components of alcohol-prevention messages, which could increase positive alcohol expectancies	Fair

Table 1 (continued)

Qureshi et al. (2019)	Break frequency	EyeLink 1000 (SR Research) Head-free infrared camera	Higher break frequency (i.e. inability to inhibit saccade) for alcohol-related stimuli and non-alcohol-related appetitive stimuli among problematic drinkers, when stimuli are presented in a peripheral (versus central) location	No control of biasing variables Median split on consumption Low control on chronic consumption	Problematic drinking is associated with reduced inhibitory control on saccadic movements towards peripheral appetitive (alcohol-related and non-alcohol-related) stimuli	Fair
Roberts et al. (2014)	Number of premature saccades Saccadic latency/accuracy	504 Eye Tracker (Applied Science Laboratory) Head-free infrared camera 60 Hz	Reduced inhibitory control during intoxication, positively correlated with chronic consumption among individuals with high bias	No control group No control of biasing variables No eye tracking measure of the attentional bias	Social drinkers present impaired saccadic latency/amplitude and inhibitory control of saccades during acute alcohol consumption	Fair
Roche and King (2010)	Saccadic latency, accuracy and velocity (saccade task) Gain (smooth pursuit)	VisualEyes VNG System (Micromedical Technologies) Head-mounted monocular camera	Stronger deficit in prosaccadic latency, accuracy and velocity in light drinkers (compared to heavy drinkers) during high alcohol intoxication	Small sample Mostly male participants	Heavy drinkers have reduced global eye movement impairment (compared to low drinkers) during high alcohol intoxication	Good
Roche et al. (2014)	Saccadic latency, accuracy and velocity (saccade task) Gain (smooth pursuit)	VisualEyes VNG System (Micromedical Technologies) Head-mounted monocular camera	Impaired gain, pro-saccade latency/velocity, and antisaccade latency/accuracy during high intoxication in heavy drinkers Preserved prosaccade accuracy/antisaccade velocity during high intoxication in heavy drinkers	No control group	Heavy drinkers present robust and reproducible eye movement impairments (impaired gain, and pro-saccade/antisaccade latency/velocity) during high alcohol intoxication	Good
Roy-Charland et al. (2017)	Time to first fixation Number of saccades Dwell time	EyeLink II (SR Research) Head-mounted infrared camera 500 Hz	No attentional bias in complex scenes during free visual exploration Attentional bias in dynamic (number of saccades) but not static measures (dwell time, initial orientation) among heavy drinkers during complex scenes memorization	Unexplained differential results across studies No control of biasing variables Limited evaluation of chronic consumption	Dynamic eye tracking indexes are better than static ones to measure attentional bias in complex scenes	Fair
Schoenmakers et al. (2008)	Initial fixation Dwell time	Eyetrace 300x (Applied Science Laboratories) Head-mounted infrared camera 120 Hz	No attentional bias among heavy drinkers without acute alcohol consumption Increased initial fixation and dwell time towards alcohol-related cues among heavy drinkers during alcohol intoxication	No control group Small sample Low control on chronic consumption No control of biasing variables	Sober heavy drinkers do not present an attentional bias. Alcohol intoxication is associated with an attentional bias in heavy drinkers	Fair

Table 1 (continued)

Sillero-Rejon et al. (2018)	Orientation of first fixation Number of fixations Dwell time	EyeLink II (SR Research)	Explicit pictures are related to increased self-reported avoidance and reactance Explicit pictures are related to increased self-reported impact on alcohol consumption No difference between moderate and explicit pictures on eye tracking indexed No impact of self-affirmation procedure	Low control on chronic consumption No manipulation check (i.e. no control for self-affirmation procedure's efficiency) Weak control on comorbidities/-biasing variables	Self-affirmation level does not impact the exploration of health warning pictures Explicit pictures are considered as more effective to reduce drinking motivation	Fair
van Duijvenbode et al. (2012)	Latency of first fixation Number of fixations Dwell time	Tobii T120 (Tobii Technology) Head-free infrared camera 60 Hz	No attentional bias in long term abstinent individuals, whatever past consumption intensity No influence of intellectual disabilities on attentional bias measures	Methodological issues in eye tracking measures Uncontrolled sample specificities (abstinence, current consumption) No control of biasing variables	Individuals with long term abstinence do not present attentional bias, independently of their past consumption or mental disabilities	Fair
van Duijvenbode, et al. (2017)	Latency/orientation of first fixation Dwell time	Tobii T120 (Tobii Technology) Head-free infrared camera 60 Hz	No behavioral attentional bias among light or heavy drinkers Attentional bias at eye tracking level (higher initial fixation and dwell times for alcohol-related stimuli), whatever consumption intensity or intellectual disabilities	No control of psychiatric comorbidities / medication Heterogeneous sample Low control on chronic consumption	Attentional bias is indexed by eye tracking (but not behavioral measures) and is independent of consumption or mental disabilities	Good
Weafer and Fillmore (2013)	Dwell time	504 Eye Tracker (Applied Science Laboratory) Head-free infrared camera 60 Hz	Heavy drinkers present an attentional bias (increased dwell time towards alcohol-related cues), correlated with the intensity/frequency of alcohol consumption Acute alcohol intoxication linearly decreases this attentional bias Stable and moderate attentional bias in light drinkers	Limited control on chronic consumption No control of biasing variables No report of behavioral correlates of attentional bias Focus on dwell time	Heavy drinkers present an attentional bias, which is reduced by alcohol intoxication	Good
Wilcockson and Pothos (2015)	Break frequency	EyeLink 1000 (SR Research) Head-free infrared camera	Slightly higher break frequency (i.e. inability to inhibit saccade towards peripheral stimulus) for alcohol-related stimuli Correlation between break frequency and weekly	No control of biasing variables Median split on consumption Heterogeneous sample	Heavy drinking is associated with reduced inhibitory control on saccadic movements towards alcohol-related stimuli	Poor

Table 1 (continued)

			consumption, particularly in males	Low control on chronic consumption		
Wilcockson et al. (2019)	Dwell time	EyeLink 1000 (SR Research) Head-free infrared camera	Attentional bias (dwell time) in heavy drinkers Correlation between attentional bias, consumption frequency/intensity and negative alcohol expectancies, but not with consumption intention, positive alcohol expectancies and craving	Limited use of eye tracking measures No control of biasing variables Low control on chronic consumption	Heavy drinking is associated with a stable attentional, independent of craving, positive alcohol expectancies and consumption intention	Fair

Legend. AAAQ, Approach and Avoidance of Alcohol Questionnaire (McEvoy et al., 2004); AUDIT, Alcohol Use Disorders Identification Test; AUQ, Alcohol Urge Questionnaire (Mehrabian and Russell, 1978); B-MAST, Brief Michigan Alcohol Screening Test (Pokorny et al., 1972); NR, Not Reported; QFI, Quantity-Frequency Index (Cahalan et al., 1969); SCID, Structured Clinical Interview for DSM-IV; TLFB, Timeline Follow-Back (Sobell and Sobell, 1992)

Results

Global Overview of Studies Characteristics

Regarding the geographical distribution (i.e., laboratory of the first author) of the 36 papers selected, 38.9% were performed in North America (13 in the United States of America, one in Canada), 52.8% in Europe (15 in the United Kingdom, three in the Netherlands, and one in France), and 8.3% in Asia (three studies in South Korea). Publication dates indicate a strong trend towards an increase of publications during the last decade, as 5.6% of the studies were published between 2000 and 2004, 8.3% between 2005 and 2009, 38.9% between 2010 and 2014 and 47.2% between 2015 and 2019. A large majority of the studies were: (1) cross-sectional, only six presenting an interventional design based on drug administration (Childs et al., 2012), cognitive remediation (Jones and Field, 2013; Lee and Lee, 2015) or brief interventions (Choi and Lee, 2015; Kersbergen and Field, 2017; Sillero-Rejon et al., 2018), and none proposing longitudinal measures; (2) focused on the experimental exploration of cognitive processes, as only one study measured emotional processes (Claisse et al., 2016) and six addressed prevention/intervention topics among participants presenting alcohol intoxication (Childs et al., 2012) or drinking habits (Choi and Lee, 2015; Harris et al., 2009; Kersbergen and Field, 2017; Monk et al., 2017a; Sillero-Rejon et al., 2018). Most studies combined behavioral (i.e., accuracy, reaction times) and eye tracking measures, only one using both eye tracking and neuroscientific techniques (i.e., event-related potentials, Iacono et al., 2000). Finally, eye tracking measures were mostly related to dwell time (assessed in 72.2% of the studies), saccade latency (36.1%), orientation and amplitude (i.e., distance between saccade's starting and ending locations) of initial saccade (44.4%) or number of saccades/fixations (22.2%). Some studies also proposed alternative measures like gain (i.e., participant's eye velocity compared to the target's velocity during smooth-pursuit) or pupillary diameter.

Quality Assessment

The quality assessment tool indicated that 31 studies were evaluated as having fair methodological quality (scoring between 51% and 69%), four as having good quality (scoring below 70% and 79%), and only one as presenting poor quality (scoring below 50%). The strength of the studies should be underlined, as all of them had clear research objectives, and the vast majority proposed a well-designed experimental paradigm with a controlled comparison between alcohol-related and neutral stimuli, or between light and heavy drinkers. Moreover, nearly all studies used established paradigms (mainly the visual probe task for attentional bias measure) and focused on widely-used eye tracking indexes (mostly dwell time). Several works also proposed innovative measures (e.g., pupillary diameter) and explored various populations (heavy drinkers, problematic drinkers or patients with severe AUD). All studies reported the brand and type of their eye tracker, and all the models used can be considered as valid eye tracking materials. However, several studies did not report the eye tracking setting (i.e., head-mounted or head-free) nor the sample rate. Among those that reported the sample rate, large variations were observed (from 60 Hz to 1000 Hz), which can lower inter-studies comparability. As the tasks used in most studies (e.g., visual probe task) require a very high temporal resolution, those proposing the lowest sample rates might have a reduced ability to record fine-grained variations in the temporality of eye tracking indexes, thus lowering the reliability of their results. Moreover, the main limitations of these studies were: (1) the low control of population characteristics and biasing variables, as most studies recruited their sample in the general population, with very limited inclusion/exclusion criteria and weak control of addictive, psychiatric, neurological or other medical comorbidities; (2) the absence of sample size justification or statistical power computation; (3) the limited evaluation of alcohol consumption habits, usually performed through classical tests only estimating recent and global alcohol consumption, and thus ignoring long term alcohol consumption pattern and specific drinking habits (e.g., binge drinking).

Main Outcomes

The use of eye tracking in populations with excessive alcohol consumption has been massively focused on the exploration of the attentional bias towards alcohol-related stimuli, as 61.1% of the studies explored this topic. Four studies measured the impact of alcohol use on the executive processes related to eye movements, and three explored perceptive impairments. Finally, one study measured emotional processes through pupillary dilatation, and six studies focused on the visual exploration of prevention messages or the implementation of interventions.

Perceptive Abilities

Three studies have offered indirect (as they mostly explored alcohol intoxication) insights regarding the influence of alcohol consumption on perceptive processes. First, King and Byars (2004) showed that heavy drinking habits did not significantly modulate the impairment observed during high alcohol intoxication for saccadic latency and velocity (measured in a prosaccade task), as well as for smooth-pursuit abilities. The only group difference was that heavy drinkers were mostly impaired for perceptive abilities during the late part of the blood alcohol concentration's rising phase, while the impairment in light drinkers was higher during the initial rising phase. Roche and King (2010) compared basic eye movements in light and heavy drinkers during three distinct alcohol intoxication intensities. They showed that the intensity/frequency of alcohol consumption did not modulate the ocular impairment under alcohol intoxication, characterized by altered smooth-pursuit gain as well as saccadic latency, velocity, and accuracy. However, this impairment was lower among heavy drinkers than light drinkers, suggesting that the tolerance resulting from heavy drinking reduces the visuomotor impairments induced by alcohol intoxication. Roche et al. (2014) reported different results as they showed impaired smooth-pursuit gain and saccadic efficiency in intoxicated heavy drinkers, together with preserved prosaccade accuracy and antisaccade velocity (which had been found impaired in the previous study).

Attentional Bias

Most eye tracking studies conducted among alcohol drinkers explored the alcohol-related attentional bias, which has been largely documented in behavioral studies (Fadardi et al., 2016; Field and Cox, 2008) and constitutes a key component of the current models of addiction (Field et al., 2010; Wiers et al., 2015a).

Four studies exploring attentional bias were conducted among alcohol drinkers during intoxication. These studies used the classic visual probe task, based on the simultaneous presentation of an alcohol-related image (a picture of an alcohol drink) and a control stimulus (a picture of a non-alcoholic drink). These two stimuli are followed by the presentation of a target (usually an arrow pointing upside or downside, a crosshair or a dot) to be processed, alternatively appearing at the same position than the alcohol-related or non-alcohol related image. Attentional bias is evidenced if the participant is faster to process the target when it appears at the same position than the alcohol-related image, as it suggests that more attentional resources were attributed to this image. Eye tracking indexes are considered useful to determine the processes underlying such preferential processing as they measure gaze behavior during stimuli presentation (e.g., more frequent initial fixation on the alcohol-related cue, higher number of fixations, and higher dwell time). Schoenmakers et al. (2008) offered the first exploration of attentional bias through eye tracking measures. No attentional bias was shown among sober heavy drinkers, but alcohol intoxication led to the emergence of an attentional bias: alcohol-related pictures were more frequently targeted by the initial fixation and associated with longer dwell times than control ones. These eye tracking indexes were positively correlated with behavioral measures of the bias, showing a good coherence across indexes. However, a more recent study (Miller and Fillmore, 2011) obtained opposite results: sober heavy drinkers showed an attentional bias, and this bias remained constant whatever the alcohol intoxication intensity. Fernie et al. (2012) confirmed the presence of a strong attentional bias among heavy drinkers, independent of alcohol intoxication. A last study (Weafer and Fillmore, 2013) obtained results which are coherent with the two previous ones: heavy drinking is associated with an attentional bias even in the absence of alcohol intoxication, this bias being proportional to the frequency and intensity of alcohol consumption. However, these authors showed that the bias is negatively correlated with alcohol intoxication, suggesting that attentional bias would play a role in the initiation of drinking episodes but not in their perpetuation once initiated. This conclusion is, however, at odds with previous results (Fernie et al., 2012; Miller and Fillmore, 2011; Schoenmakers et al., 2008).

Ceballos et al. (2009) performed the first study specifically exploring attentional bias using eye tracking measures among alcohol drinkers, independently of alcohol intoxication. They used a free exploration paradigm during which images (alcohol-related stimuli, household objects, or both) were presented. Results showed significant positive correlations between alcohol consumption (only estimated by a quantity-frequency index) and eye tracking indexes. This demonstrates a link between alcohol consumption's frequency-intensity and the automatic (indexed by the initial fixation) and controlled (indexed by dwell time) components of alcohol-related bias. Miller and Fillmore (2010) compared the bias related to simple (isolated alcohol-related cue) and complex (alcohol-related cue inserted in an elaborated scene) images. They showed that the attentional bias was present at both behavioral and eye tracking levels only with simple images. The lack of attentional bias towards complex scenes might be due to the fact that such complex stimuli require the processing of non-alcohol-related features and increase the need for visual search and scan, which could lower the capture of attentional resources by alcohol-related stimuli. The authors also proved that eye tracking constitutes a more robust evaluation of attentional bias than behavioral measures, the effect size of attentional bias indexed by dwell time being twice as large as the one measured through reaction times. Capitalizing on these seminal results, three lines of research have then been developed, respectively exploring the modulation of the attentional bias by internal task-related or external alcohol-related factors, by participants' characteristics, and by attentional training.

First, Field et al. (2011) determined how alcohol expectancies can modulate the attentional bias. They used a free exploration task with alcohol/neutral pairs of images. Alcohol expectancy was modulated at the beginning of each trial by a message indicating the probability (0, 50, or 100%) of receiving a small amount of beer after the trial. This modulation of alcohol expectancy did not modify the attentional bias among heavy drinkers. Conversely, the attentional bias was only present when alcohol expectancies were high among light drinkers. In other words, the attentional bias appeared stable in heavy drinkers, while it depended on current expectancies in light drinkers. A second study (Jones et al., 2012) explored whether the influence of alcohol expectancies was specific for alcohol-related cues or generalized towards other appetitive stimuli. They used the same probabilistic procedure together with attentional bias measure but applied it to alcohol and chocolate in a within-subject design. For both stimuli, increased expectancy was associated with higher attentional bias, and this effect was not substance-specific. The expectancy to receive a reward thus globally increased the attentional bias towards appetitive cues. Lee et al. (2014) explored the influence of ambivalence towards alcohol (i.e., the simultaneous presence of approach and avoidance tendencies) on attentional bias. Hazardous drinkers with or without ambivalence towards alcohol were compared during the free exploration of alcohol/neutral pictures pairs. Both groups presented an attentional bias at early processing stages, this bias being even higher in the ambivalent group. Conversely, only the non-ambivalent individuals presented higher dwell times and an increased number of fixations towards alcohol-related pictures. It thus appears that, while all hazardous drinkers have an increased early attentional capture by alcohol-related stimuli, the bias related to more controlled attentional processes disappears when an ambivalence towards alcohol emerges. A recent study (Wilcockson et al., 2019) addressed a related topic by measuring, in a within-subject design, the modification of attentional bias in heavy drinkers by current consumption intention. A significant alcohol-related bias was found again, and this bias was positively correlated with the intensity/frequency of alcohol consumption but was not influenced by consumption intention. Moreover, the attentional bias was correlated with negative expectancies towards alcohol, but not with positive ones or craving. These results, coherent with previous ones (Field et al., 2011), suggest that the attentional bias in heavy drinkers is robust and not influenced by fluctuant internal factors. Another study (Christiansen et al., 2015a) focused on the modulation of attentional bias by task characteristics. They compared the reliability of the visual probe task between behavioral versus eye tracking measures on the one hand, and between standardized versus personalized stimuli on the other hand. In line with previous results, they showed that the reliability of the task was higher when using eye tracking measures (dwell time), and when using personalized stimuli compared to standardized ones, the combination of both increasing reliability up to .76. Beyond reliability, results also demonstrated that personalized stimuli increased the magnitude of the attentional bias at the behavioral level.

Second, a series of studies explored to what extent participants' stable traits can modify the attentional bias. Van Duijvenbode et al. (2012) first explored the variation of the attentional bias according to the intensity of alcohol-related problems and intellectual disabilities. Surprisingly, they observed that various levels of alcohol consumption (light, moderate, heavy drinkers) and intellectual impairments (average, borderline, mild intellectual disability) were not related to any bias at behavioral or eye tracking levels. This research group more recently addressed (Van Duijvenbode et al., 2017) the same question with a similar methodology, but ended up with different conclusions. Indeed, they identified a significant alcohol-related bias for eye tracking measures in a large sample of participants grouped according to their IQ and alcohol consumption. The intensity of this bias did not differ according to these variables, and the bias was not significantly correlated with alcohol consumption and craving measures. While the presence of a bias contradicts the results of the previous study, the present one confirmed that the intensity of alcohol consumption and intellectual disabilities do not influence attentional bias. The large heterogeneity of the sample, the disputable cut-off scores used for alcohol consumption, and the inter-individual variability in the measured attentional bias, however, call for caution when interpreting those results. The generalization of the attentional bias beyond healthy adult samples has also been explored among adolescent heavy drinkers (McAteer et al., 2015). In a free visual exploration task, this population showed a significant increase in dwell time for alcohol-related stimuli when compared to light or non-drinkers, but no attentional bias was observed (as dwell time was not higher for alcohol-related than neutral stimuli). Dwell time for alcohol-related stimuli was correlated with the intensity of alcohol consumption, as well as with the degree of positive expectancies towards alcohol. Although the absence of attentional bias raises questions, the authors concluded that the higher time spent on alcohol-related cues at the early stages of alcohol-related problems might be underpinned by changes in controlled (indexed by dwell time) rather than automatic processes. A cross-sectional study (McAteer et al., 2018) further explored the evolution of automatic/controlled processes related to attentional bias by evaluating this bias among young light or heavy drinkers of various ages. Results replicated the outcomes of the previous study by showing that, while heavy drinkers did not present an attentional bias per se, they presented higher dwell time for alcohol-related stimuli than light drinkers, independently of age. An increased percentage of first fixation towards alcohol stimuli was also found in young adults when compared to late adolescents. This result led to the conclusion that increasing age is related to a higher automatic capture of attentional resources. Lastly, Marks et al. (2015) explored the substance-specificity of attentional bias by comparing bias amplitude among individuals with severe cocaine use disorder, half of them presenting comorbid severe AUD. A visual probe task presenting cocaine or alcohol-related stimuli (paired with neutral ones) was used, and results showed that the attentional bias is specific to the substance used (i.e., a cocaine-related bias for cocaine users, and an alcohol-related bias among patients with severe AUD). Attentional bias thus appears specific to the substance used rather than constituting a global approach tendency towards all appetitive stimulations. Unfortunately, this study did not include a group of patients presenting severe AUD without joint cocaine consumption, limiting its impact on alcohol-related literature.

Third, only one study (Lee and Lee, 2015) used eye tracking measures to determine the modifications of eye movements resulting from attentional bias modification. This technique (Schoenmakers et al., 2010) implements a contingency in the visual probe task, leading participants to learn that focusing attentional resources on the non-alcohol-related cue increases task performance. This procedure thus progressively creates a counter-bias by training individuals to disengage attention from alcohol-related stimuli. Attentional training had been widely applied in alcohol-related disorders at the behavioral level (e.g., Clerkin et al., 2016; Rinck et al., 2018), but its eye tracking correlates remained unexplored. Lee and Lee (2015) showed that attentional training among problematic drinkers indeed reduced attentional bias. However, such training did not modify ambivalence towards alcohol, which suggests that attention bias modification does not act upon the explicit evaluation of alcohol consumption.

Finally, several studies have gone beyond the classical visual probe task to develop new eye tracking measures of attentional bias. Hobson et al. (2013) proposed an alcohol version of the flicker paradigm for inducing change blindness (Jones et al., 2002; Simons and Levin, 1997), in which participants have to detect a brief change in components of a complex picture. The probability of detecting this change increases for components leading to a capture of attentional resources, and an alcohol-related bias is thus objectified by the better detection of changes concerning alcohol-related stimuli. Two versions of the alcohol flicker task were used among individuals presenting various alcohol consumption patterns. Higher alcohol consumption and higher craving were associated with an increased percentage of alcohol-related changes detection. While proposing a potential alternative to the visual probe task, the flicker paradigm has not yet been used in other eye tracking studies, and its comparative strengths/drawbacks remain to be clarified. Wilcockson and Pothos (2015) proposed a gaze contingency paradigm measuring the ability to inhibit the orientation of attentional resources towards alcohol-related stimuli in peripheral vision. The participant was asked to keep watching a fixation target and to refrain from producing a saccade towards the neutral or alcohol-related stimuli appearing in other parts of the screen. The dependent measure was the comparison of "break frequency" rates (i.e., the number of times a participant looked at the peripheral stimulus) related to neutral and alcohol-related stimuli. A significant correlation was found between alcohol-related break frequency and weekly alcohol consumption, particularly among males, offering preliminary support to the proposal that this task might be useful to measure the inhibitory processes related to attentional bias. A recent study (Qureshi et al., 2019) also used a gaze contingency paradigm with alcohol-related, appetitive non-alcohol-related, and non-appetitive stimuli. They observed a higher break frequency towards alcohol-related stimuli among regular drinkers, but this result was also observed for non-alcohol-related appetitive pictures. These results suggest that the attentional bias is not specifically related to alcohol stimuli. These two studies thus support the interest of the gaze contingency paradigm, but the specific psychometric and experimental value of this task remains to be demonstrated. Two other studies recently developed more ecological procedures to measure attentional bias. Roy-Charland et al. (2017) proposed a dynamic exploration of eye movements, by analyzing the global pattern of saccadic movements produced by drinkers when seeing complex visual scenes (with or without alcohol cues). A first experiment showed an absence of alcohol-related bias during the free visual exploration of the scenes, no correlation between eye tracking indexes and alcohol consumption being reported. Conversely, a second experiment, in which participants were asked to memorize the visual scene, demonstrated a positive correlation between alcohol consumption and the number of in/out saccades towards alcohol-related stimuli. The authors proposed that the number of saccades, by offering insights on the dynamic structure of visual exploration, is a better index than static measures (e.g., dwell time) to evaluate alcohol-related bias, as it measures the tendency of drinkers to have their attentional resources systematically drawn back to alcohol-related stimuli. Monem and Fillmore (2017) proposed a more innovative approach by switching from the classical presentation of static pictures to the exploration of attentional bias in a natural environment. In this study, a portable eye tracking device was combined with video recording while participants freely explored, during two sessions, a recreational room containing objects, soft drinks, and alcoholic beverages. No attentional bias was observed during the first session but, during the second one, a habituation effect was found for soft drinks (i.e., reduced dwell time) but not for alcohol stimuli, indicating an alcohol-related bias (correlated with alcohol consumption intensity). Beyond offering an ecological way to explore real-life attentional bias, this study brought further support to the proposal that the alcohol-related bias mostly relies on controlled processes (i.e., sustained attention towards alcohol stimuli) rather than on automatic ones (i.e., the capture of attentional resources when first confronted with alcohol stimuli).

Executive Functions

Four studies directly explored executive control in alcohol drinkers through eye tracking measures. The first one focused on the identification of the neurobehavioral correlates of substance use risk in adolescents, and thus gave only limited insights regarding eye movements. Indeed, Iacono et al. (2000) determined the predictive value of combined event-related potentials (P300 measure), electrodermal response modulation, and eye tracking (antisaccade task) indexes regarding the risk to develop substance use disorder in male adolescents. Participants identified as being at high-risk according to neurobehavioral indexes showed an increased frequency of alcohol and nicotine dependence in comparison with moderate or low-risk groups, which suggests that these indexes have a significant predictive value. As the only results presented regarding the antisaccade task were the error rates (i.e., the proportion of wrong saccades, without mentioning other eye tracking measures), this study does not bring new data about eye movements in at-risk individuals. A second study (Roberts et al., 2014) explored the eye movements related to inhibitory control in a delayed ocular response task among regular drinkers, but the authors were mostly interested in the modulation of this inhibitory control by alcohol intoxication. In this task, participants had to fixate a central point, then a peripheral distractor stimulus appeared and they were told to refrain any saccade towards the distractor, as long as the fixation point remained on screen. After the disappearance of the fixation point, participants had to perform a saccade at the previous location of the distractor. By measuring the ability to delay a reflexive saccade towards a salient stimulus, this task evaluates the inhibitory control of attention, premature saccades indexing failed inhibition. This study showed a positive correlation between alcohol consumption and inhibitory control's impairment during alcohol intoxication, particularly among individuals presenting a strong alcohol-related bias (evaluated by the visual probe task). The simultaneous presence of decreased inhibitory control (during alcohol intoxication) and attentional bias (during alcohol-related processes) is thus associated with increased consumption, which is in line with the dual-process model. Two studies more directly explored the eye movements related to executive functions in alcohol drinkers, independently of alcohol intoxication. Laude and Fillmore (2015) explored how alcohol-related stimulations can alter inhibitory association learning in frequent drinkers. They used a conditioned inhibition task, consisting of: (1) A training phase, where a conditioned inhibitor stimulus (S1) is presented together with a second stimulus (S2), this joint presentation being followed by an absence of reinforcement so that the participant learns the conditioned "inhibitor–no outcome" association. Then, the second stimulus (S2) as well as a third one (S3) are presented alone and repeatedly associated with an outcome; (2) A test phase, assessing the degree to which S1 has been encoded as a conditioned inhibitor by asking the participant to rate the probability of having an outcome when S3 is presented alone or paired with S1. If S1 has been encoded as a conditioned inhibitor following the training phase, the probability of outcome should be evaluated as lower when S3 is presented simultaneously with S1. To measure the impact of alcohol-related cues on conditioned inhibition, alcohol-related and neutral cues were compared when used as S2, and eye movements were measured during the training phase. Attentional bias (visual probe task), working memory (letter memory task), and self-reported impulsivity were also measured as control variables. A reduced conditioned inhibition related to S1 was shown when S1 had been coupled with alcohol-related stimuli (compared with neutral cues) in the training phase. Moreover, this was associated with a higher dwell time for alcohol-related cues in the training phase, suggesting that, when alcohol stimuli are used in the training phase, they capture the attentional resources and reduce the dwell time on the conditioned inhibitor (S1), thus reducing conditioned inhibition learning. A significant alcohol-related bias was also shown, but it did not influence conditioned inhibition. As a whole, this study demonstrates that the hijack of attentional resources by alcohol-cues can interfere with the acquisition of new associations and thus reduce learning efficiency. A last study on this topic (Jones and Field, 2013) explored to which extent alcohol-related cues modulate the efficiency of an intervention program training inhibition to reduce alcohol consumption. A first experiment focused on motor inhibition (trained through a modified stop-signal task) while a second one, using eye tracker measures, proposed a training of oculomotor inhibition using a prosaccade/antisaccade task. An alcohol/saccadic type contingency was introduced so that participants of the "alcohol restraint" group had to perform a prosaccade towards the picture in 80% of the neutral stimuli trials, and an antisaccade away from the picture in 80% of the trials with alcohol-related images (this contingency being reversed in the "neutral restraint" group). The first experiment showed that using alcohol-related stimuli instead of neutral cues when training motor inhibition led to a reduction of immediate alcohol consumption (i.e., free drinking in a bogus taste test after the experiment) but did not influence later alcohol consumption. Conversely, no improvement of inhibition training efficiency through the use of alcohol-related cues was shown for oculomotor inhibition, as the only effect of alcohol cues was to slow down prosaccades towards alcohol cues, without any effect on subsequent alcohol consumption. The efficiency of inhibition training is thus not strongly improved by the use of alcohol cues instead of neutral ones.

Emotion

Claisse et al. (2016) explored emotional processing among patients with severe AUD. As these patients present strong impairments in emotional processing (e.g., D'Hondt et al., 2014; Herman and Duka, 2019), they used pupil diameter (indexing the automatic modulation of the autonomous system) to measure emotional reactivity in patients presenting short- and long- term abstinence. When presented with positive or negative emotional scenes, patients and matched controls showed the expected increased pupillary diameter, but this increase was amplified among patients with short-term abstinence. Moreover, patients also presented this effect for neutral scenes, suggesting an over-reactivity of the autonomous system, independently of the affective content of the stimuli. The duration of abstinence was positively correlated with a decrease in pupillary response to emotional stimuli, suggesting a progressive rehabilitation of the autonomous system with abstinence. The absence of matching between groups (age, gender, social level) and the lack of control of biasing variables (e.g., medication, other drug consumption) reduce the extent of these conclusions.

Prevention/Intervention

Six studies explored the effects of prevention or intervention programs on eye movements in populations of drinkers. First, Harris et al. (2009) explored how contextual elements (namely the complementary visual components presented together with prevention messages but unrelated to the message's content) influence the processing of actual prevention messages. They presented internet sites proposing prevention messages, accompanied by contextual elements presenting low (advertisements) or high (trust seal) credibility. The credibility of accompanying elements did not modulate the dwell time on the message, but participants spent more time looking at content-irrelevant parts of the site in the low credibility condition. Importantly, the influence of the prevention message on subsequent alcohol consumption was stronger in the high credibility condition, particularly among women with heavy alcohol consumption. Second, Monk et al. (2017a) measured the eye movements of heavy drinkers when confronted with alcohol warning messages (composed of an image and a prevention text) and explored the influence of image type by comparing arousing or neutral images. Results showed higher dwell time for image than text, independently of image type. They also demonstrated that visual exploration interacts with alcohol expectancies: the increase in positive alcohol expectancies after exploring the messages was positively correlated with the dwell time towards the image. Alcohol prevention campaigns may thus have a counter-productive effect, as even negative alcohol-related images might promote positive alcohol expectancies. Kersbergen and Field (2017) evaluated the amount of attentional resources dedicated to warning labels on alcohol packaging during a memory task, and its link with changes in actual consumption. In a first study, they showed that participants pay minimal attention to such warning labels, as only 7–8% of the dwell time was focused on these labels. This dwell time was even negatively correlated with the motivation to reduce drinking. A second study showed that a short intervention aiming to boost the drinking reduction motivation did not influence the attention to warning labels. The intervention failed to reduce drinking motivation among participants. Finally, increasing the visual salience of the warning label (by adding a brightly colored border around it) did not influence dwell time. As a whole, alcohol drinkers allocate reduced attention towards warning labels on alcohol packaging, and such labels do not influence actual consumption. Recently, Sillero-Rejon et al. (2018) investigated how a short intervention boosting self-affirmation (Klein et al., 2011) modifies the processing of alcohol health warning labels, compared to a control group without intervention. After this manipulation, participants' eye movements were recorded while they explored 12 pictures of beer cans presenting either a moderate or explicit picture related to health warning, together with a written prevention message. Three eye tracking outcomes were measured (percentage of first fixations, number of fixations and dwell time on health warning pictures) together with self-reported reactions to the pictures. No difference was found between moderate and explicit pictures regarding eye movements' measures, and the self-affirmation procedure did not impact eye tracking results.

Finally, two studies proposed interventions to modulate alcohol-related factors. On the one hand, Choi and Lee (2015) tried to decrease implicit and explicit alcohol craving through a virtual reality covert sensitization procedure conducted in light and heavy drinkers using a conditioning procedure associating alcohol with aversive cues. Subjective craving was measured through the Alcohol Urge Questionnaire (Mehrabian and Russell, 1978), while implicit craving was measured through an alcohol implicit association task, an alcohol Stroop test, and eye tracking indexes (i.e., dwell time towards alcohol-related stimuli). Virtual covert sensitization significantly reduced the dwell time towards alcohol-related stimuli in both groups. This result, coherent with those observed for the other craving measures, suggests that virtual covert sensitization can efficiently reduce alcohol craving, at least in the short term. On the other hand, Childs et al. (2012) proposed a direct pharmacological intervention to reduce alcohol consumption, by exploring the potential usefulness of varenicline (a partial acetylcholine receptor agonist mostly used to reduce nicotine dependence) to increase the aversive effects related to alcohol intoxication. Varenicline was administered to social drinkers to test its impact on subjective and physiological responses to alcohol intoxication. Eye tracking measures showed that varenicline can partly reduce the impaired smooth pursuit and saccadic slowing down induced by alcohol intoxication in heavy drinkers. However, the very limited sample size (15 healthy social drinkers) hampers to draw any strong conclusion from these results.

Discussion

Synthesis of the Results

In order to sum up the main outcomes of the studies included in this review, we propose here a brief overview of the results obtained for each main category of processes. Regarding *perceptive abilities*, heavy drinkers present impaired smooth pursuit as well as saccadic latency/velocity during alcohol intoxication (King and Byars, 2004). The increased tolerance associated with drinking habits might lead to a partial reduction of these impairments (Roche and King, 2010), but heavy drinkers nevertheless present a reproducible pattern of eye movement deficits (for smooth pursuit gain and saccadic efficiency) during high alcohol intoxication (Roche et al., 2014). With regard to a*ttentional bias*, an attentional bias towards alcohol-related cues has been identified among heavy drinkers during alcohol intoxication, but results are not coherent regarding the modulation of this bias by drinking habits. It had initially been postulated (Schoenmakers et al., 2008) that this bias would be absent during sobriety, while more recent works have argued that alcohol intoxication does not influence the attentional bias in heavy drinkers (Fernie et al., 2012; Miller and Fillmore, 2011) or even reduces it (Weafer and Fillmore, 2013). In the absence of alcohol intoxication, adolescent heavy drinkers do not present behavioral attentional bias but have increased controlled attention (McAteer et al., 2015) and dwell time (McAteer et al., 2018) towards alcohol-related stimuli. Conversely, young adult drinkers present a robust attentional bias (better indexed by eye tracking than behavioral measures) for simple (but not complex) alcohol pictures (Ceballos et al., 2009; Miller and Fillmore, 2010), which appears mostly related to modifications of the high-level attentional processes (Monem and Fillmore, 2017) and to reduced inhibitory control on saccadic movements (Wilcockson and Pothos, 2015). The evaluation of the attentional bias presents increased reliability when using eye tracking indexes (compared to behavioral performance measures) and personalized stimuli (Christiansen et al., 2015a), and the attentional bias is better evidenced by dynamic eye tracking measures (Roy-Charland et al., 2017). It might be increased by reward expectancy (Jones et al., 2012), craving (Hobson et al., 2013) and low alcohol ambivalence (Lee et al., 2014), but other studies have suggested that it is independent of craving, positive alcohol expectancies (Field et al., 2011), consumption intention (Wilcockson et al., 2019), as well as actual consumption and mental disabilities (Van Duijvenbode et al., 2017). The attentional bias is absent in individuals with long term abstinence (Van Duijvenbode et al., 2012). It appears substance-specific, as it is absent in cocaine-dependent individuals (Marks et al., 2015), but it might be generalized to stimuli considered as appetitive for the participant (Qureshi et al., 2019). Bias modification training can reduce this attentional bias in problematic drinkers, this change being centrally related to an increase in controlled alcohol avoidance (Lee and Lee, 2015). Concerning *executive functions*, alcohol intoxication impairs inhibitory control of saccades (Roberts et al., 2014) in social drinkers. Independently of alcohol intoxication, adolescents at high risk for substance use have a reduced inhibitory control on eye movements (Iacono et al., 2000). The use of alcohol-related stimuli reduces conditioned inhibition learning in frequent drinkers (Laude and Fillmore, 2015) but does not influence the impact of oculomotor inhibition training on alcohol consumption (Jones and Field, 2013). Regarding *emotional processing*, a globally increased pupillary reactivity has been shown in severe AUD, but this modification might disappear with long-term abstinence (Claisse et al., 2016). Finally, for what pertains to *prevention/intervention,* alcohol drinkers pay very low attention to alcohol-prevention messages (Kersbergen and Field, 2017), as they focus their attentional resources on visual rather than textual components of messages (Monk et al., 2017a). Content-irrelevant cues can modulate the influence of these messages on alcohol consumption (Harris et al., 2009). Virtual covert sensitization can reduce attentional bias and craving towards alcohol (Choi and Lee, 2015), but increased self-affirmation does not impact the visual exploration of explicit health warning pictures (Sillero-Rejon et al., 2018). Finally, varenicline might reduce the eye movement deficits induced by high intoxication in heavy drinkers (Childs et al., 2012).

Limits of the Current Literature

Population Studied and Alcohol-Related Measures

Most reviewed studies (33/36) focused on subclinical populations (i.e., described their experimental sample as social, heavy, or problematic drinkers). The three eye tracking studies performed among patients with severe AUD either mixed these patients with subclinical populations (Van Duijvenbode et al., 2017), only included patients with comorbid addictive disorder (i.e., cocaine use disorder, Marks et al., 2015) or only reported a specific eye tracking index (i.e., pupillary diameter; Claisse et al., 2016). There is thus an urgent need to develop eye tracking studies in severe AUD, as it constitutes the alcohol consumption pattern associated with the most intense neurocognitive consequences (Le Berre et al., 2017; Stavro et al., 2013). Eye tracking indexes could thus, in line with what has been done in subclinical populations, renew the neurocognitive exploration of severe AUD, and lead to theoretical (e.g., by proposing complementary insights on the imbalance between reflective and reflexive systems), experimental (e.g., by offering innovative measures of the cognitive processes and of their brain correlates) and clinical (see below) implications. Regarding subclinical alcohol consumption, eye tracking studies are inconsistent regarding the terminology, evaluation, and thresholds that were chosen to categorize alcohol consumption patterns. Various terms are used across studies (e.g., "heavy drinking", "problematic drinking", "binge drinking", "hazardous drinking"), reducing inter-studies comparisons. Moreover, the sample is often poorly specified, most studies recruiting participants in the general population and only offering global evaluations of alcohol consumption [i.e., AUDIT (Saunders et al., 1993) or Brief Michigan Alcohol Screening Test (Pokorny et al., 1972)] and potential biasing variables (e.g., psychopathological comorbidities, other addictive states). Finally, most studies neglected the interaction between alcohol intoxication and drinking habits. Indeed, studies focusing on alcohol intoxication frequently overlooked the global alcohol consumption pattern, and conversely, studies exploring eye movements among regular drinkers did not control for potential alcohol intoxication during the experiment. The studies disentangling the respective impacts of alcohol intoxication and drinking habits on eye movements have underlined the presence of strong interactions between these factors but led to contradictory results (Fernie et al., 2012; King and Byars, 2004; Miller and Fillmore, 2011; Roche et al., 2014; Roche and King, 2010; Schoenmakers et al., 2008; Weafer and Fillmore, 2013).

Processes Measured and Eye Tracking Indexes

Only a limited set of cognitive functions (mostly attentional bias and inhibition) have been assessed through eye tracking measures among alcohol drinkers. No study has used eye tracking tools to explore perceptive or memory abilities and only one has investigated emotional processing (Claisse et al., 2016), despite its key role in severe AUD (Sliedrecht et al., 2019). The use of eye tracking measures should thus be extended towards these processes. At the methodological level, all studies capitalized on the hypothesized link between eye tracking indexes and their underlying cognitive processes. However, the discrepancy between the measures taken and the cognitive abilities at stake should be considered. Eye tracking measures three main indexes, namely gaze location, eye movements' characteristics (i.e., fixation, saccade, pursuit, blink), and eye-related parameters (e.g., pupil diameter). These indexes do not constitute the uncontaminated reflect of cognitive functions, because (1) various bottom-up (brightness, colors) or top-down (memory, expectations) factors modify eye movements; (2) eye tracking focuses on foveal vision, but the peripheral retina also processes visual stimuli, impacting subsequent foveal analysis (D'Hondt et al., 2013). Valid conclusions regarding the cognitive processes related to eye movements are thus possible only when the paradigm and eye tracking indexes have been carefully selected. This is particularly true for dwell time: The basic assumption behind dwell time is that it reflects the time spent watching specific parts of the stimuli, and thus the attentional resources or bias dedicated to these parts. However, increased dwell time can also be related to uncontrolled variables as cognitive processing difficulty (Rayner et al., 1978), drowsiness or low arousal (Chapman and Underwood, 1998). Moreover, in attentional bias paradigms, dwell time is usually interpreted as the controlled processing of attention maintenance. However, some authors interpreted reduced dwell time as reflecting lower automatic attentional capture by the substance (Lee and Lee, 2015). Conversely, many studies considered initial fixation or saccadic latency as indexing automatic attentional capture, as they are fast and early. However, automatic processes are not always fast, as they can be triggered after a delay. Furthermore, in visual probe tasks, stimuli are presented in a peripheral location, the distance from the screen center varying across studies, while visual discrimination performance decreases linearly with eccentricity (Thorpe et al., 2001). Studies on this topic are also mostly conducted among participants of Western cultures, who scan elements from left to right (Dickinson and Intraub, 2009; Foulsham et al., 2013; Zelinsky, 1996). In visual search paradigms, participants thus typically start their exploration on the left, even when the target is located on the right (Nuthmann and Matthias, 2014). This systematic left-to-right scanning lowers the potential effect of stimuli content on the first fixation orientation. Finally, the reviewed studies largely vary regarding the eye tracking's sample rate and the algorithms used to categorize eye movements as fixations or saccades, which might also have influenced the results. As a whole, future studies should question the statement that each eye tracking index undisputedly reflects a single cognitive process, to offer a more thorough description of their results.

Experimental and Clinical Perspectives

Experimental Perspectives

Improving Alcohol Consumption Evaluation A key priority for future studies is to propose a sound and standardized alcohol consumption evaluation, ensuring sample homogeneity, controlling for potentially biasing variables, and improving inter-studies comparability. As several earlier studies used the AUDIT and TLFB, these two tools could constitute the minimal alcohol consumption measures, potentially complemented by items: (1) estimating the long-term consumption pattern (e.g., age at first drink, global lifetime intensity/frequency of consumption); (2) evaluating more specific drinking habits (e.g., binge drinking; Townshend and Duka, 2002, 2005). As many earlier studies reported very high AUDIT levels in their sample, a significant proportion of participants considered as subclinical heavy drinkers might have presented undiagnosed severe AUD. Future studies on subclinical alcohol consumption should thus ensure the absence of severe AUD in their sample (e.g., through the evaluation of the 11 DSM-5 criteria).

A second way to increase inter-studies comparability is to standardize the terms used to label the experimental group presenting AUD. The literature on subclinical AUD is indeed characterized by the wide variety of the terms used to qualify experimental groups, and this problem is also found in the eye tracking studies included in this review. In view of the current literature, the following proposal can be made regarding this issue: "binge drinking" should be used to qualify people presenting a specific alcohol consumption pattern characterized by intense episodic intakes with high consumption speed and high drunkenness frequency (as indexed by a binge drinking score higher than 16, Townshend and Duka, 2005); "heavy drinking" should be used for individuals presenting a binge drinking pattern (at least four/five units consumed per occasion), but with an increased frequency (i.e., more than once per week, NIAAA, 2004); "hazardous drinking" should refer to a repetitive pattern of alcohol consumption already leading to health consequences, consisting of the consumption of at least five (women) or seven (men) doses per occasion, at a minimum of three times per week. This pattern can be identified by AUDIT scores above eight (Palfai and Ostafin, 2003; Van Tyne et al., 2012). Lastly, social drinking is mainly based on drinking context and motivations, and captures excessive drinkers (most of the time according to weekly alcohol consumption, e.g., Townshend and Duka, 2002) but without systematic evaluation of drinking motives or alcohol expectancies (Petit et al., 2012). This term, together with the unclear "problematic drinking" label, should thus be avoided in future work.

Controlling for alcohol intoxication is also a priority, to check that the remaining consequences of recent intoxications do not contaminate the eye tracking correlates of heavy drinking (e.g., Roche and King, 2010; Schoenmakers et al., 2008). Such recent consumption could be controlled by confirming the absence of current intoxication (using a blood alcohol concentration measure) and by excluding people who consumed alcohol in the preceding days (as the cognitive effects of intoxication can last for several days, Stephens et al., 2014). Future studies should also evaluate psychiatric (depression, anxiety) and addictive (nicotine, cannabis consumption) comorbidities, as these factors influence cognition (e.g., D'Hondt et al., 2018) and eye tracking measures (Armstrong and Olatunji, 2012; Rycroft et al., 2005; Wilcockson and Sanal, 2016). Finally, as underlined above, eye tracking explorations should be applied to severe AUD. Future studies should capitalize on the well-established evaluation of severe AUD, encompassing DSM-5 diagnosis criteria but also other alcohol-related characteristics influencing cognitive impairments (e.g., severe AUD duration, alcohol consumption before detoxification), as well as psychiatric comorbidities. Moreover, these studies should respect the standard guidelines promoted in this research field by testing recently detoxified patients who are no more in the acute withdrawal period and who have remained abstinent for at least two weeks.

Understanding the Underlying Processes and Improving Eye Tracking Measures As most earlier studies did not report sample size justification or statistical power computation and were based on quite limited sample sizes, the first global advice for future work is to provide a priori power analyses and to capitalize on larger samples, ensuring the reliable detection of existing effects. More specifically, regarding eye tracking measures, a key recommendation is to evolve towards the standardization of the designs used. While the search for innovative paradigms has been initiated, the establishment of uniform and sound designs specifically evaluating each cognitive process, together with valid eye tracking measures, would allow a valid comparison across studies. Such homogenization has been accomplished regarding attentional bias paradigms, most studies using the visual probe task. The eye tracking measurements during this task are useful to characterize the specific attentional components involved when people face alcohol-related and non-alcohol-related stimuli. Keeping in mind the limits raised in the previous section, there is nevertheless a need to determine guidelines for measuring attentional bias. Indeed, despite the use of the same paradigm, some methodological choices differ across studies (e.g., using an arrow, a crosshair, or a dot as targets, leading to discrepancies in participant's task), which could decrease inter-studies comparability. More centrally, the eye tracking indexes measured strongly vary across studies, attentional bias having been assessed by: (1) averaging the mean fixation time on each stimulus (e.g., Monem and Fillmore, 2017); (2) calculating the proportion of fixation time or of numbers of fixations made on each stimuli category (e.g., Lee et al., 2014); (3) calculating a bias score by subtracting the average dwell time on neutral stimuli from the average dwell time on alcohol-stimuli (e.g., Marks et al., 2015); and (4) counting the number of fixations made on each stimuli (e.g., Roy-Charland et al., 2017). These different methods for calculating a seemingly identical construct can explain incongruences across results, and methodology could thus be optimized to unravel the mechanisms sustaining this attentional bias: first saccade direction or first saccade latency can inform on the initial orientation of attention; first fixation duration on early attentional engagement; total dwell time on attentional maintenance; number of fixations on attentional reengagement. Future studies should also carefully select the non-alcoholic stimuli used in attentional bias paradigms, by proposing control stimuli presenting a similar appetitive valence to alcohol-related ones. Indeed, several earlier studies compared highly-appetitive alcohol cues with low-appetitive neutral cues, the attentional bias towards alcohol thus being potentially related to the higher appetitive value of alcohol stimuli (independently of their alcohol-related nature), as recently suggested (Monk et al., 2017b; Pennington et al., 2019; Qureshi et al., 2019). Regarding the possibility to interpret the nature of the attentional bias as either automatic or controlled, it appears relevant to contrast conditions where exploration of alcohol-related stimuli is allowed with conditions where participants are explicitly told to refrain looking at these stimuli, as recently proposed in new paradigms (Wilcockson and Pothos, 2015). It remains, however, unknown whether these paradigms offer a methodological and experimental added value in comparison with the visual probe task.

Regarding the use of eye tracking to assess other cognitive functions, the recent open-source protocol developed by Nij Bijvank et al. (2018) offers the opportunity to conduct studies following a standardized procedure across alcohol-related disorders. This protocol encompasses several tasks exploring perceptive, working memory or inhibition abilities, and is thus a promising proposal for the emergence of standardized protocols with modules targeting specific cognitive processes. In alcohol-related disorders, this would be especially crucial for emotional and interpersonal difficulties. They indeed remain poorly understood and understudied using eye tracking measurements, despite the existence of reliable eye tracking paradigms to explore them (e.g., Black et al., 2017; Blais et al., 2017; Niu et al., 2012). Overall, a strong advantage of developing one single protocol that would combine modules targeting different processes relies on the possibility to correlate the performances assessed through standardized measures between different tasks (e.g., perceptive/emotional or emotional/cognitive). Such a procedure allows considering a deficit evidenced in one task in the light of other potential difficulties. This aspect is particularly relevant regarding alcohol-related disorders, which are associated with visuoperceptive impairments interfering with other cognitive abilities (Creupelandt et al., 2019). Of note, pupil diameter was seldom used in studies among alcohol drinkers (Ceballos et al., 2009; Claisse et al., 2016), although this measure is an interesting and complementary index of cognition and emotion, for instance informing about mental effort or emotional arousal (Eckstein et al., 2017). Future studies should use this ocular measure, providing a particular caution in the way data are measured, analyzed, and interpreted since pupil diameter is a metric that is complex to use adequately (see Mathôt et al., 2018 for guidelines).

Finally, the necessity to ensure sufficient reliability in eye tracking measures is crucial for correlational studies where the upper bound of the observable correlations depends on the reliability of both variables. Low between-subject variability causes low reliability for individual differences, hampering the likelihood to observe replicable correlations with other factors and potentially undermining published conclusions drawn from correlational relationships. This might be one of the reasons why results regarding correlations between attentional bias measures and other measures such as age, IQ or craving, are not consistent across studies, and why null correlations are observed despite sometimes being theoretically highly plausible. The reliability of the eye tracking measurements should thus be estimated and reported mandatorily before interpreting significant or non-significant correlations with other variables.

To conclude, we believe those recommendations are important to consider in order to better understand the underlying processes and accurately conclude on alterations specifically associated with alcohol-related processes or disorders. They are also mandatory to optimize the application of the eye tracking technique in clinical settings, for longitudinal follow-up as well as therapeutic interventions (Nij Bijvank et al., 2018).

Clinical Perspectives

We have shown the current paucity of eye tracking studies focused on interventional designs among alcohol drinkers, as only four studies have addressed therapeutic questions. The first one (Childs et al., 2012) used eye tracking indexes to determine the impact of a medication (varenicline) on alcohol intoxication in heavy drinkers. While offering potential clinical avenues by showing that varenicline can partly reduce the eye movements' impairments following alcohol intoxication, this study does not appear to present a direct impact on the treatment of severe alcohol-related disorders. The study by Choi and Lee (2015) underlined the potential usefulness of virtual reality to reduce alcohol craving through covert sensitization, but no specific effect on heavy drinking was shown, and its influence on actual alcohol consumption has not been tested. Conversely, the two other studies explored the eye tracking correlates of cognitive remediation in heavy drinkers, and thus offered preliminary insights regarding the use of eye tracking in clinical settings.

First, Lee and Lee (2015) showed that attentional training can reduce the alcohol-related bias in heavy drinkers, through an increase in the inhibitory control of eye movements. This study, by underlining that the change produced through training might be mostly related to the controlled rather than automatic processes involved in the attentional bias, proposed the first eye tracking insights in attentional training. Attentional bias modification programs have attracted much interest in the clinical field (Gladwin et al., 2016). Based on initial experimental results (e.g., Schoenmakers et al., 2010), attentional training is currently spreading in clinical settings worldwide. However, while many studies still consider attentional bias modification as a promising therapeutic tool, and while this technique is now also applied in subclinical populations (Wiers et al., 2015b), its clinical relevance has been recently questioned (Christiansen et al., 2015b). The actual impact of behavioral attentional training on clinical outcomes thus appears modest (Boffo et al., 2019; Schoenmakers et al., 2010) or even inexistent (Cristea et al., 2016). This deceiving effectiveness can be partly due to the very low internal reliability of the visual probe task, widely used in attentional bias studies but criticized concerning its psychometric qualities (Ataya et al., 2012). Beyond the recent proposals to increase the validity of the behavioral measures related to this task (Evans and Britton, 2018), the use of eye tracking indexes could improve the internal reliability and validity of the task. Indeed, behavioral measures such as reaction times only indicate where participant's attention is oriented when the cues disappear, while eye tracking measures provide insights into the time course of eye movements and the processes involved in attentional bias. Eye tracking thus simultaneously increases the task's internal reliability (Christiaensen et al., 2015a) and leads to a more reliable estimation of this bias (Field and Cox; 2008; Popa et al., 2015). Eye tracking measures could moreover help to identify the underlying processes involved in attentional bias modification, and thus guide future improvements of attentional training procedures.

Second, Jones and Field (2013) offered a proof of concept that eye tracking measures can be used to rehabilitate executive functions. Using an oculomotor inhibition training procedure, they showed that immediate post-training alcohol consumption can be reduced through increased control of eye movements towards alcohol-related cues. These preliminary data in heavy drinking should be complemented by more controlled training procedures in severe AUD, but they might initiate the development of eye tracking-based intervention programs focusing on inhibition, which is considered as one of the main factors contributing to the maintenance of addictive disorders. Innovative paradigms could be experimentally tested to propose efficient inhibition training, for example by using the break frequency index (Qureshi et al., 2019; Wilcockson and Pothos, 2015) or gaze contingency procedures to boost attentional control and inhibition (Lazarov et al., 2017; Vazquez et al., 2016).

Neuropsychological remediation only recently emerged in clinical settings treating alcohol-related disorders, and the current priority is obviously to generalize this approach by proposing a standardized and empirically-based evaluation battery of behavioral tasks encompassing attentional, executive, but also emotional and interpersonal processes (Rochat et al., 2019), and by implementing a rational pattern of remediation (Rolland et al., 2019). It might thus appear premature to propose an expanded use of eye tracking measures in clinical settings. However, future experimental studies should clarify the usefulness of eye tracking measures to evaluate and rehabilitate cognitive deficits in alcohol-related disorders, in order to determine the most efficient paradigms and indexes, thus paving the way for the future inclusion of eye tracking in clinical practice.

Conclusion

This paper had two main objectives. The first was to propose a comprehensive review of the available literature regarding eye tracking measures in alcohol drinkers. The second was to offer, based on a critical appraisal of the available literature, new research avenues for improving the use of eye tracking indexes among these populations, as well as methodological guidelines for future studies. We decided to focus on peer-reviewed studies and thus did not include grey literature, which might constitute a bias (as unpublished results were not considered here). However, the systematic review considered all eye tracking indexes (i.e., saccade amplitude, latency, velocity, gain, initial fixation, number of fixations, dwell time, pupillary diameter, as well as more innovative indexes like gaze contingency) exploring all cognitive processes (i.e., perceptive abilities, attentional bias, executive functions, emotion, prevention messages processing) among alcohol drinkers. This integrative synthesis led to conclude that subclinical alcohol-related disorders are associated with: (1) impaired ocular perceptive/motor abilities, particularly during alcohol intoxication; (2) a widely established attentional bias, indexed by increased dwell time for alcohol-related stimuli, but the interactions between alcohol intoxication and drinking habits regarding this bias remain to be clarified; (3) lowered inhibitory control on eye movements; (4) increased pupillary reactivity to visual stimuli, regardless of their emotional content; (5) a very limited visual attention to prevention messages (even in the absence of alcohol intoxication) which raises serious doubts regarding the impact of prevention campaigns. This review also underlined the current shortcomings of this field, and centrally the fact that severe AUD has been nearly totally ignored by eye tracking studies, the only available results among patients with severe AUD but without comorbidity showing an increased pupillary reactivity, independent of the type of visual stimulation and which appears to decrease with prolonged abstinence (Claisse et al., 2016). Moreover, most studies only proposed limited control on alcohol intoxication or drinking habits as well as limited use of eye tracking indexes, thus lowering the strength of their conclusions. Capitalizing on the identification of these limits, we have proposed crucial perspectives for future research, accompanied by methodological guidelines, to promote gold standards for upcoming studies. These proposals claim for generalizing the use of improved alcohol consumption evaluation as well as more specific and innovative eye tracking indexes, to address some unexplored questions (centrally related to severe AUD) but also to clarify the current debates (notably concerning the joint influence of alcohol intoxication and drinking habits on attentional bias or executive functions). The evolution of this field towards an optimized use of eye movements' measures across the whole spectrum of alcohol consumption habits should help eye tracking to become a key tool in the exploration of alcohol-related disorders, by contributing to their experimental exploration and theoretical conceptualization. Beyond alcohol-related disorders, eye tracking explorations have recently emerged in other addictive states like nicotine (e.g., Baschnagel, 2013; Lochbuehler et al., 2018), cannabis (e.g., Alcorn et al., 2019; Yoon et al., 2019), cocaine (e.g., Dias et al., 2015; Strickland et al., 2018) or gaming/gambling use (e.g., Kim et al., 2019; McGrath et al., 2018), showing similar results than those reported in the present review. Some deficits indexed with eye tracking tools (e.g., modified cue salience, reduced inhibitory abilities) might thus constitute transdiagnostic processes, and studies directly comparing eye movements' characteristics across addictive disorders should be promoted.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

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