Table 1a Summary of the included and critically reviewed publications on behavioural measures.

Publication	Animal-based indicator	Environmental variables	No. of animals	No. of institutions	Experimental design	Method of assessing welfare or other focus of study	Reliability	Validity
Altman 1999	Object manipulation [%], activity *, inactive [%]	*Enrichment objects*	2 (0.2)	1	Experimental (own control); repeated treatments (ABAB); quantitative	Monitored behavioural changes following provision of non-edible manipulative objects	None reported	Criterion
Ames 1993 (various case-studies)	Stereotypy *[s%] Foraging * aggressive interactions [%] anticipation [s%] proximity [s%], Activity level [s%], activity [%], inactivity [%] Rubbing, feeding, lying, digging, object manipulation	*Feeding enrichment, substrate, group composition, feeding interval (feeding and starve days*)	14 (6.8)	7	Experimental; own control; observational; repeated measures; quantitative	Monitored behavioural changes following changes to the environment, over time (seasons) and compared activity budgets to wild conspecifics	None reported	Criterion
Ames 1994	Object manipulation [s%], substrate preference [s%]	*Object and feeding enrichment, substrate*	14 (6.8)	7	Observational; descriptive; quantitative	Monitored behavioural change over time (seasons) and substrate preference	None reported	-
Canino & Powell 2010	Pacing [%], object play [%], rest [%], activity budget	*Enrichment novelty (object)*	1 (1.0)	1	Experimental; own control; repeated treatments (ABAB); quantitative	Monitored behavioural differences between provision of novel and previously used enrichment items	None reported	Criterion
Cless *et al* 2015	Pacing, gait (step cycle and head height) *, locomotion	-	11 (4.7)	7	Observational; quantitative	Assessed whether pacing is quantifiably different from non-repetitive locomotion	None reported	Criterion
Cless & Lukas 2017	Pacing location [c], pacing intensity * anticipatory nature [c]*, gait (step cycle)	-	10	7	Observational; survey questionnaire; quantitative; qualitative	Assessed intensity and frequency of pacing and investigated underlying motivation	None reported	Criterion
Cremers & Geutjes 2012	Stereotypic behaviour *, active, inactive [%], attentiveness	*Feeding interval (feeding and starve days)*, keeper presence*, presence of conspecific*, noise level, enrichment items, substrate, exhibit traffic, employee count*	1 (1.0)	1	Observational; quantitative	Investigated how environmental factors affect behaviour	None reported	Criterion

Table 1a (continued)

Publication	Animal-based indicator	Environmental variables	No. of animals	No. of institutions	Experimental design	Method of assessing welfare or other focus of study	Reliability	Validity
Folk *et al* 1973	Heart rate[%] (sleep budget, feeding, drinking, sitting, walking, standing)	-	2 (2.0)	1	Case report; descriptive	Investigated bradycardia	-	-
Forthman *et al* 1992	Abnormal behaviour [%], active *, passive*	*Feeding enrichment**	2 (1.1)	1	Experimental; own control; repeated treatments (ABAB); quantitative	Investigated effect of feeding enrichment on behaviour	IOR	Criterion
Hein *et al* 2020	Faecal glucocorticoid metabolites (FGM)* [c], social tension [c]	*Environmental change**, *various disturbances**, *animal transport**	8 (4.4)	12	Questionnaire; quantitative,	Validated a cortisol enzyme immunoassay and determined individual long-term FGM levels (in context of season and social relations)	None reported	Construct Criterion
Kelly *et al* 2014	Stereotypic behaviour [s%], inactivity [s%], activity [s%], activity budget	*Visitor density*	3 (1.2)	1	Observational; descriptive; quantitative	Monitored how behaviour change according to season, social and environmental factors	IOR	-
Kuczaj *et al* 2002	Object interaction	*Enrichment item, variable presentation of enrichment*	1 (1.0)	1	Experimental; own control; repeated measures; quantitative	Investigated effect of variable presentation of enrichment objects on behaviour	None reported	Criterion
Kutska 2009	Stereotypic behaviour *, interaction with enrichment items*	*Naturalistic and un-naturalistic enrichment items*	2 (1.1)	1	Experimental; own control; repeated measures; survey questions	Investigated visitor perceptions of enclosure (and behavioural response of polar bears) in response to provision of naturalistic and un-naturalistic enrichment items	None reported	-
Linder *et al* 2020	Stereotypic behaviour*, activity in water*, inactivity*, activity on land, social play	*Novel odour objects**	2 (0.2)	1	Experimental; own control; repeated measures; quantitative	Investigated application of behavioural instability as a tool for behavioural responses	None reported	Criterion
Poulsen *et al* 1996	Pace [%], facial tic (abnormal) [%], coughing/huffing (abnormal) [%], non-stereotypical mobility [%], immobility [%], sleeping [%]	*(Drug administration)*	1 (0.1)	1	Experimental; own control; repeated treatments (ABA), quantitative; qualitative	Monitored behavioural changes following drug administration (fluoxetine)	None reported	-

Table 1a (continued)

Publication	Animal-based indicator	Environmental variables	No. of animals	No. of institutions	Experimental design	Method of assessing welfare or other focus of study	Reliability	Validity
Renner & Kelly 2006	Aggressive interactions, non-aggressive interactions, inter-individual distance	-	2 (0.2)	1	Observational; descriptive, quantitative	Investigated how polar bears manage inter-individual distance	None reported	-
Ross 2006	Stereotypic behaviour *, pacing *, social play *, swimming *, object manipulation, feeding, locomotion, attention to staff	*Off-exhibit access*	2 (1.1)	1	Experimental; own control; repeated measures; quantitative	Monitored behavioural changes following changes to the environment (off-exhibit access)	IOR	Criterion
Shepherdson *et al* 2004	Stereotypic behaviour *, FGM *	-	48 (22.26)	18	Epidemiological; observational; survey; questionnaire; quantitative; qualitative	Assessed differences in corticoid profiles of stereotypic bears and non-stereotypic bears	None reported	-
Shepherdson *et al* 2013	Pace [c], FGM [c], temperament [c], time budget	*Animal transport, view out of exhibit*, enclosure size (dry land)*, enrichment and diversity*, no. of bears in group*, positive reinforcement training program*	55 (24.31)	20	Epidemiological; observational; experimental (novel object test); quantitative	Assessed relationship between environmental variables, temperament, stereotypic pacing and FGM	IOR	Construct Criterion
Wechsler 1991	Stereotypic behaviour, yawning, tongue-flicking, time budget, walking, sitting, lying, attentiveness, swimming		3 (1.2)	1	Observational; descriptive; quantitative; qualitative	Investigated spatial and temporal patterns of stereotypies and whether stereotypies reduce arousal level	None reported	-
Wechsler 1992	Stereotypy [%], walking, standing, inactivity, sniffing *, attentiveness	*Odour marks*	2 (1.1)	1	Experimental; own control; repeated measures; quantitative	Investigated motivation behind stereotypic behaviour	None reported	Criterion

% : Percentage change in unit during study or between groups, not subjected to statistical analysis.
* : Statistically significant change in unit during study, between groups significant or association with environmental factors.
c : Correlation or other significant relationship with animal-based indicators identified during the study.
s: Seasonal change.
Abbreviations: IOR: Inter-observer reliability, FGM: Faecal glucocorticoid metabolite concentration, ABA and ABAB: Repeated treatments design, AB: Repeated measures design, A: Baseline, B: Experimental (Swaisgood & Shepherdson 2005).

Table 1b Summary of the included publications on physical and physiological measures (not critically reviewed).

Publication	Animal-based indicator	Environmental variables	No. of animals	No. of institutions	Experimental design	Method of assessing welfare or other focus of study	Reliability	Validity
Abdelgawad *et al* 2014	Loss of appetite, heavy salivation, difficult breathing, saliva sampling	-	1 (1.0)	1	Case report	Zebra-borne equine herpesvirus type 1)	-	Content
Alroy *et al* 1980	Weight loss, skin abscesses, reduced appetite, reduced activity, blood values	-	1 (1.0)	1	Immunohistochemically case study	Case of multiple beta cell neoplasms	-	Content
Baba *et al* 2013	Stool (diarrhoea), vomiting, blood biochemical parameters	-	1 (1.0)	1	Case report	Crescentic Glomerulonephritis (kidney syndrome)	-	Content
Banks *et al* 1999	Anorexia, pruritus, vomiting, stool (diarrhoea)	-	3 (1.3) + other bears	1 (circus)	Case reports	Aujeszky's disease (herpesvirus 1)	-	Content
Dayaram *et al* 2018	Loss of appetite, stool (diarrhoea), tissue and blood sampling	-	1 (1.0)	1	Case report	Mastadenovirus	-	Content
Deem & Calle 2001	Lameness, foot abscess, tooth rot abscess (stereotypic behaviour)	-	1 (0.1)	1	Case report	Cellulitis and abscess formation	-	Content
DiVincenti *et al* 2019	Anorexia, blood values	-	1 (0.1)	1	Case report	*Babesia* sp. infection	-	Content
Donovan *et al* 2009	Muscle tremors, erratic circling, increased blinking, head shaking, ptyalism, flexor rigidity, less responsive to stimulus	-	1 (0.1)	1	Case report	Meningoencephalitis	-	Content
Dutton *et al* 2009	Non-moving hind limb, anorexic, serum antibodies	-	1 (1.0)	1	Case report	Paraparesis	-	Content
Eo & Kwon 2014	Skin condition, coat condition, reluctance to swim, scratching	-	1 (0.1)	1	Case report	Dermatitis	-	Content
Fortin & Benoit-Biancamano 2014	Body condition	-	1 (1.0)	1	Case report	Pancreatic islet cell tumor	-	Content
Garner *et al* 1997	Anorexia	-	2	1	Case report	Hepatic sarcocystosis	-	Content

Table 1b (continued)

Publication	Animal-based indicator	Environmental variables	No. of animals	No. of institutions	Experimental design	Method of assessing welfare or other focus of study	Reliability	Validity
Kenny *et al* 1998	Vitamin levels (D, E, A, 5-OH-D) (sera, skin and milk)	-	36 captive (56 free-ranging)	6	Observational	Determined reference vitamin levels and compared levels of captive to free-ranging polar bears	-	Content
Kenny *et al* 2004	Hind limb weakness	-	1 (0.1)	1	Case report	Describing myasthenia gravis	-	Content
Lacasse *et al* 2006	Inappetence, tussis, dysphagia	-	1 (1.0)	1	Case report	Tracheitis, *Bordetella bronchiseptica*	-	Content
LaDouceur *et al* 2014	Vomiting, weight loss, alopecia, inappetence, polyuria–polydipsia, lameness, tooth and gum condition, skin condition, pruritus, abnormal rapid breathing, ataxia, pedal abscess, azotemia, anemia, hyperphosphatemia, isosthenuria, biochemical abnormalities	-	11 (1.10)	8	Retrospective study	Investigating end-stage-renal-disease	-	Content
Lin *et al* 2005	Vitamin D (25-OHD) serum levels, bone health, non-weight bearing limb	-	4 (2.2)	4	Retrospective, observational	Described fracture repair and 25-OHD levels	-	Content
Mendez-Angulo *et al* 2014	Vomiting, blood parameters	-	1 (0.1)	1	Case report	Omental torsion	-	Content
Monson *et al* 2014	Stool (chronic diarrhoea), stool quality	-	1 (1.0)	1	Case report	Feed trial (food allergy)	-	Content
Morris *et al* 1989	Anorexia, weight loss, hind leg weakness	-	1 (1.0)	1	Case report	Describing systemic blastomycosis	-	Content
Morrison *et al* 2017	Gait limitation, weight loss	-	1 (0.1)	1	Case report	Lumbar stenosis	-	Content
Smith & Cordes 1972	Lesions, fur loss, alopecia, matted, discoloured and dirty fur, scratching, reluctance to swim	-	6 (3.2.unknown)	1	Case report	Dermatitis caused by *Dermatophilus congolensis*	-	Content

Table 1b (continued)

Publication	Animal-based indicator	Environmental variables	No. of animals	No. of institutions	Experimental design	Method of assessing welfare or other focus of study	Reliability	Validity
Stamper *et al* 1999	Fur condition (urine scalding)	-	1 (1.0)	1	Case report	Hypospadias	-	Content
Velguth *et al* 2009	Body condition, vomiting, restlessness, muscle wasting	-	3 (3.1)	3	Case reports	Describes cases of umbilical hernias	-	Content
Zimmerman *et al* 2010	Non-bearing weight on limb, blood count	-	1 (0.1)	1	Case report	Fracture	-	Content

Table 2a Summary of the identified behavioural indicators and the respective association with other animal-based parameters and/or effect of interventions or influence of environmental factors.

Indicator	Identified in	Change or association	Correlated or associated with (AB)	Affected by (RB and/or MB)	Reported reliability	Evidence of validity
Abnormal behaviour	Ames 1993 Canino & Powell 2010 Cless & Lukas 2017 Cless *et al* 2015 Cremers & Geutjes 2012 Forthman *et al* 1992 Kelly *et al* 2014 Kutska 2009 Linder *et al* 2020 Poulsen *et al* 1996 Ross 2006 Shepherdson *et al* 2013 Shepherdson *et al* 2004 Wechsler 1992 Wechsler 1991	**Ames 1993** **Cremers & Geutjes 2012** **Kutska 2009** **Linder *et al* 2020** **Ross 2006** **Shepherdson *et al* 2013** **Shepherdson *et al* 2004** Canino & Powell 2010 Forthman *et al* 1992 Kelly *et al* 2014 Poulsen *et al* 1996 Wechsler 1992	**FGM+** **(Temperament: slow-to-approach)+** **(interest)-)**	**Feeding -** **Naturalistic enrichment items (vs non-naturalistic items) -** **Odour marks -/+** **Off-exhibit access -** **View out of exhibit -** **No. of bears in group -** **Positive reinforcement training -** Novel enrichment items - Starve days + Keeper presence - Noise (over 70dB) + Feeding enrichment - Visitor density -/+ Drug administration (fluoxetine) -	IOR (seasonal change)	Construct Criterion
Activity	Altman 1999 Ames 1993 Forthman *et al* 1992 Kelly *et al* 2014 Linder *et al* 2020	**Altman 1999** **Forthman *et al* 1992** **Linder *et al* 2020** Ames 1993 Kelly *et al* 2014	None	**Enrichment objects +** **Feeding enrichment +** **Odour marks +**	IOR (seasonal change)	Criterion
Anticipation	Ames 1993 (Cless & Lukas 2017)	**(Cless & Lukas 2017)** Ames 1993	**Pacing intensity +**	**Pacing location (holding doors) +** Feeding strategy	None	Criterion
Attentiveness	Cremers & Geutjes 2012 Ross 2006 Wechsler 1991 Wechsler 1992	None	None	Off-exhibit access +	None	None
Feeding and foraging	Ames 1993 Folk *et al* 1973 Ross 2006	**Ames 1993**	Heart rate	**Feeding enrichment +**	IOR	Criterion
Inactivity	Altman 1999 Ames 1993 Cremers & Geutjes 2012 Forthman *et al* 1992 Kelly *et al* 2014 Linder *et al* 2020 Poulsen *et al* 1996 Wechsler 1992	**Forthman *et al* 1992** **Linder *et al* 2020** Altman 1999 Ames 1993 Cremers & Geutjes 2012 Kelly *et al* 2014 Poulsen *et al* 1996	None	**Feeding enrichment -/0** **Odour marks +** Object enrichment - Substrate + Visitor density -/+ Drug administration (fluoxetine) +	IOR (seasonal change)	Criterion

Table 2a (continued)

Indicator	Identified in	Change or association	Correlated or associated with (AB)	Affected by (RB and/or MB)	Reported reliability	Evidence of validity
Locomotion	Cless *et al* 2015 Poulsen *et al* 1996 Ross 2006 Wechsler 1991 Wechsler 1992	Poulsen *et al* 1996	None	Drug administration (fluoxetine) (+)	IOR	None
Object manipulation and play	Kutska 2009 Ames 1994 Altman 1999 Canino & Powell 2010 Ames 1993 Kuczaj *et al* 2002 Ross 2006	**Kutska 2009** Ames 1994 Altman 1999 Canino & Powell 2010	None	**Naturalistic enrichment items (vs non-naturalistic items)** + Object enrichment + Novel enrichment items +	IOR (seasonal change)	Criterion
Rest and sleep	Canino & Powell 2010 Poulsen *et al* 1996	Canino & Powell 2010 Poulsen *et al* 1996	None	Object enrichment - Drug administration (fluoxetine) (+)	None	Criterion
Sniffing (investigation)	Wechsler 1992	**Wechsler 1992**	None	**Odour marks** +	None	Criterion
Swimming	Ross 2006 Wechsler 1991	**Ross 2006**	None	**Off-exhibit access +**	IOR	Criterion
Social play	Ross 2006	**Ross 2006**	None	**Off-exhibit access +**	IOR	Criterion
Social aggression/tension	Ames 1993 Hein *et al* 2020 Renner & Kelly 2006	**Hein *et al* 2020** Ames 1993	**FGM +**	Mechanical feeder +	None	Construct
Social behaviour (other)	Ames 1993 Renner & Kelly 2006	None	None	None	(Seasonal change)	None

Bold text indicates significant findings (non-bold indicates % change not subjected to statistical analysis).
Effect/relationship with indicator is indicated by: + : positive relationship, - negative relationship, 0 no observed change/effect in conjunction with '/' to indicate separate contradicting findings between individuals or studies.
Abbreviations: AB: Animal-based, RB: Resource, MB: Management-based, IOR: Inter-observer reliability.

Table 2b Summary of the identified physical and physiological indicators and the respective association with other animal-based parameters and/or effect of interventions or influence of environmental factors.

Indicator	Identified in	Change or association	Correlated or associated with (AB)	Affected by (RB and/or MB)	Reported reliability	Evidence of validity
Appetite	Abdelgawad *et al* 2014 Alroy *et al* 1980 Banks *et al* 1999 Dayaram *et al* 2018 DiVincenti *et al* 2019 Dutton *et al* 2009 Garner *et al* 1997 Lacasse *et al* 2018 LaDouceur *et al* 2014 Morris *et al* 1989	NA	NA	Various health issues	NA	Content
Body condition and weight	Alroy *et al* 1980 Fortin & Benoit-Biancamano 2014 LaDouceur *et al* 2014 Morris *et al* 1989 Morisson *et al* 2017 Velguth *et al* 2009	NA	NA	Various health issues	NA	Content
Dental condition	Deem & Calle 2001 LaDouceur *et al* 2014	NA	NA	Health issue	NA	Content
FGM	Hein *et al* 2020 Shepherdson *et al* 2013 Shepherdson *et al* 2004	**Hein *et al* 2020** **Shepherdson *et al* 2013** **Shepherdson *et al* 2004**	**Social tension+** **Pacing +** **Temperament (interest) -**	**Animal transfer +** **Environmental change +** **Various disturbances +** **Enclosure size (dry land) -**	(No seasonal change)	Construct Criterion
Gait and limb problems	Donovan *et al* 2009 Deem & Calle 2001 Dutton *et al* 2009 Kenny *et al* 2004 LaDouceur *et al* 2014 Lin *et al* 2005 Morris *et al* 1989 Morrison *et al* 2017 Zimmerman *et al* 2010	NA	NA	Various health issues	NA	Content
Heart rate	Folk *et al* 1973	Folk *et al* 1973	None	None	None	None

Table 2b (continued)

Indicator	Identified in	Change or association	Correlated or associated with (AB)	Affected by (RB and/or MB)	Reported reliability	Evidence of validity
Haematological and biochemical parameters	Alroy *et al* 1980 Abdelgawad *et al* 2014 Baba *et al* 2013 Banks *et al* 1999 Dayaram *et al* 2018 DiVincenti *et al* 2019 Dutton *et al* 2009 Kenny *et al* 1998 LaDouceur *et al* 2014 Lin *et al* 2005 Mendez-Angulo *et al* 2014 Morris *et al* 1989 Zimmerman *et al* 2010	NA	NA	Nutritional deficiencies, various health issues	NA	Content
Pedal condition	Deem & Calle 2001 LaDouceur *et al* 2014	NA	NA	Health issue	NA	Content
Skin and coat condition	Alroy *et al* 1980 Eo & Kwon 2014 Smith & Cordes 1972 LaDouceur *et al* 2014 Stamper *et al* 1999	NA	NA	Various health issues	NA	Content
Stool quality	Baba *et al* 2013 Banks *et al* 1999 Dayaram *et al* 2018 Monson *et al* 2014	NA	NA	Various health issues	NA	Content

Bold text indicates significant findings (non-bold indicates % change not subjected to statistical analysis).
Effect/relationship with indicator is indicated by: + : positive relationship, - negative relationship.
Abbreviations: AB: Animal-based, RB: Resource, MB: Management-based, IOR: Inter-observer reliability, NA: Not assessed in this review.

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