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Cognitive archaeology: estimating the effects of blood-lead concentrations on the neuropsychological function of an officer of the 1845 Franklin expedition

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Abstract

Lead poisoning has been implicated in the loss in the Arctic of all 129 officers and men of the British Royal Naval "Franklin expedition" of 1845. In a unique study, D'Ortenzio et al. (2018) estimated blood-lead concentrations of an officer of the expedition over the three months prior to his death which is thought to have occurred before the desertion of the expedition's ships. The present study applies regression coefficients which quantify the relationship between blood lead and neuropsychological function to the data of D'Ortenzio et al. to estimate whether the officer's lead exposure would have impaired his cognitive performance in the critical period prior to the desertion. It is shown that the blood-lead concentrations would have been associated with only small deficits in higher-order cognitive processes including attention, visual scanning, memory and decision-making which would not have been of functional significance. Greater deficits were associated with psychomotor functions involving eye-hand co-ordination and fine motor control which, although not defined formally as "impairment", might have affected accuracy when using firearms or operating instruments relevant to the scientific objectives of the expedition. The study also reviews evidence that the levels of lead in the Franklin crew, while high relative to today, were typical of those of the lead-exposed Victorian population from which they were recruited. The results contribute to evidence that lead exposure did not play a significant role in the loss of the Franklin expedition.

Keywords

Franklin expedition, lead intoxication, cognitive impairment

1. Introduction

1.1 Context and aim

High concentrations of lead are present in the soft tissues and skeletal remains of the one-hundred-and twenty-nine officers and men of the Royal Navy's "Franklin Expedition" of 1845 which met a fatal end in the Arctic. The early supposition that the crew suffered lead poisoning from contamination of their canned provisions is not supported by recent evidence that lead had accumulated over the men's lifetimes prior to joining the expedition and did not increase during the mission.

Whilst lead poisoning may not have caused the loss of the expedition, exposure to the metal is associated with impaired cognitive function. It is then material to determine the deficit, if any, associated with concentrations of lead found in the crew in light of speculation that it may have affected the decision-making of officers. Until recently, such analysis has been impossible because it requires knowledge of the concentration of lead in the blood, but no free blood has been recovered from the crew's remains. Now, D'Ortenzio et al. (2018) have estimated blood lead from the hair of an officer of the expedition to describe his exposure to the metal over three-months prior to his death.

The study will first review evidence that a significant proportion of the Franklin crew would have had long-term exposure to lead which pre-dated the expedition and whose levels are similar to those of present-day groups with occupational exposure. The established relationship between blood lead and cognition in those groups will be applied to estimate the effects of blood-lead concentrations defined by D'Ortenzio et al. (2018) upon the cognitive function of one of the expedition's officers.

1.2. Brief historical background: the loss of the Franklin expedition

The history of the Franklin Expedition has been described in great detail (Beattie and Geiger, 2004; Cyriax, 1939; Lambert, 2009; Palin 2018; Potter 2016; Savours, 1999) so that only significant events are summarised here. In May 1845, HM Ships *Erebus* and *Terror* departed from England under the command of Captain Sir John Franklin to gather data on Arctic magnetic variation and establish a Northwest Passage to the Pacific Ocean. After

wintering at Beechey Island where three men died, the expedition proceeded southwest until beset in heavy ice north-west of King William Island in September 1846. In May 1847, a senior officer recorded that the status of the expedition was "*All Well*". However, the ships remained beset and were deserted in April 1848: by then, nine officers and fifteen men had died since leaving England, including Sir John Franklin. The one-hundred-and-five survivors intended to trek south to the estuary of Back's Fish River on the Canadian mainland.

It was supposed that the men succumbed to scurvy and starvation during the trek and that most were dead by winter 1848 and all by summer 1849 (Wordie and Cyriax, 1953). However, the wrecks of *Erebus* and *Terror* were found in 2014 and 2016, respectively, far south of their position when deserted in 1848. Their discovery, and the testimony of Inuit people who met crewmen in 1850 (Rae, 1854), would support Woodman's (2015) conclusion that the ships were re-manned and that some men survived until 1850 or 1851.

In the 1980s, the analysis of skeletal remains on King William Island and *post mortem* examinations of the men buried on Beechey Island found high concentrations of lead in bone and soft tissue (Beattie and Geiger, 2004). It was concluded that the crew had suffered lead poisoning which played a significant role in the loss of the expedition.

1.3. Lead in the remains of the Franklin crew

When ingested or inhaled, lead that is not excreted is distributed in blood to the bones and soft tissues where, in the tibia, it has a half-life of 48.6 years (Wilker et al., 2011) and is a marker of cumulative exposure. Levels of lead in the remains of the Franklin crew are high relative to those in the present-day British population (Amy et al. 1986; Beattie, 1985; Keenleyside et al 1996; Kowal et al. 1989, 1991; Notman et al 1987). Initially, the lead was concluded to have derived from lead solder which sealed, and supposedly contaminated, the canned provisions (Beattie and Geiger, 2004), or from lead pipes supplying drinking water (Battersby and Carney, 2011; Carney, 2016) such that half of the total skeletal lead burden accumulated during three years of the expedition (Keenleyside et al., 1996). The crew were supposed to have been incapacitated by lead poisoning which contributed to the loss of the expedition.

The hypothesis runs counter to evidence of low or nil lead contamination of canned provisions supplied to other Royal Naval Arctic crews (Banfield, 1960; Drummond and Lewis, 1939). Moreover, no signs and symptoms of lead poisoning are found in the medical records of crews sent in search of the missing expedition and who ate similar canned provisions and drank on-board water (Millar et al. 2016). More significantly, synchrotron radiation X-ray fluorescence imaging (SR-XFI) of the distribution and concentration of lead in skeletal material and nail of crewmen (Martin *et al.* 2013; Christensen et al 2017) shows significant exposure prior to joining the expedition that did not increase during the mission. Swanston et al. (2018) have shown further that the distribution of lead in dental cementum confirms life-long exposure and that patterns of lead in cortical bone microstructure were very similar between men who died early in the expedition and those who died some two years later. Swanston et al. (2018) observe that the findings do not support the conclusion that lead exposure was crucial to the loss of the expedition. Moreover, lead in the remains of contemporary non-Arctic Royal Naval personnel confirms the ubiquity of high exposure in crews that operated in other environments (Giffin et al 2017; Swanston *et al*. 2016, 2018).

The above evidence is consistent with Farrer's (1993) conclusion that lead concentrations in the crew simply reflected those of the Victorian population from which they were recruited and which had very high exposure to lead relative to today. All social classes were at risk, both on land and at sea, from multiple sources including environmental pollution, adulterated food and wine, water supplies, tableware and medicines (Curtin, 1989; Millar and Bowman, 2017; Troesken 2006; Wohl, 1984). Evidence of this exposure is found in levels of lead in tooth enamel primarily from second premolar and second molar teeth of individuals who lived in and around 19thcentury London and Coventry (Millard et al., 2014). Enamel in the latter teeth is formed between approximately 2.5 and 6.5 years of age and reflects lead exposure during childhood Millard et al., 2014). Concentrations were "high to extremely high" compared to present-day populations and with some individuals having "higher levels of childhood lead exposure than any others reported in the literature" (Millard et al., 2014 p294, 296). This high exposure in childhood presumably reflects that of the

population as a whole, although greater exposure was observed amongst affluent urban dwellers than poor and rural communities. The problem began to be addressed with the "Adulteration of Food, Drink and Drugs Act" of 1872 and the "Prevention of Lead Poisoning Act" of 1883, but it was only after a Home Office enquiry into lead poisoning in 1911 that the Admiralty contracted for crockery with leadless or low-solubility lead glaze (Jarrett and Thompson 2012).

The levels of lead in the Franklin crew therefore reflect those of the Victorian population and other Royal Naval crews. Most significantly for the present study, the levels of lead in the tibiae of the crew are also similar to those in present-day groups with occupational exposure to lead (see Millar et al, 2015; Morrow et al. 2007; Schwartz et al., 2005). This equivalence with modern groups is important because a quantitative negative relationship has been established between their cognitive function and cumulative lead exposure measured in the tibia and acute exposure measured in blood. The outcome of those studies will be applied to estimate the effect of lead upon the cognitive function of an officer of the expedition.

1.4. Blood lead: physical and mental effects

Exposure to lead has long been recognised as harmful to health (Montgomery et al., 2010). Blood lead denotes current exposure from the exogenous sources described above, and endogenously from long-term skeletal storage (D'Ortenzio et al., 2018; Morrow et al., 2007). Gastric and neurological symptoms become more likely as blood-lead increases above 40μgPb/dl but inter-individual variation in tolerance means that substantially higher levels may not cause debility (Kosnett et al., 2007; Milković-Kraus et al., 1997) and clinical symptoms may not be seen below 60 μgPb/dl (Needleman, 2004). Victorian physicians also observed this wide variation in tolerance to lead where mild, non-specific symptoms could be passed off as every-day ailments (Elliotson, 1839; Harrison, 1852). It can then be supposed that some Royal Naval crewmen, as in the population as a whole, experienced subtle physical and mental consequences of lead exposure (Millar et al 2016).

Lead has an early influence upon intellectual potential. Blood-borne lead is transported across the placenta and crosses the blood-brain barrier (Hu et al., 2007) so that for many in Victorian Britain the exposure of the brain would have begun *in utero* and continued throughout life. The adverse consequences for early brain development (Dobbs 2009; Jedrychowski et al., 2009; Needleman, 2004) persist into adulthood (Stewart and Schwartz, 2007) as one of many factors that prevent an individual achieving their inherent cognitive potential (Lezak et al., 2012). The wide-spread exposure to lead in Victorian Britain would imply that significant numbers were denied their full potential although the effects would commonly have been subtle and without impairing everyday function. Moreover, factors including higher childhood cognitive ability, longer education and greater occupational attainment confer a "cognitive reserve" which maintains cognitive performance when the brain is subject to pathology that may cause dysfunction. Cognitive reserve protects the function of individuals with occupational exposure to lead (Bleecker et al., 2007) and is significant to the present investigation.

Research with present-day, occupationally-exposed cohorts who have accumulated similar lead burdens to the Franklin crew has applied regression analysis to establish a quantitative negative relationship between performance of neuropsychological tests and acute lead exposure measured in blood and cumulative exposure measured in the tibia (Dorsey et al., 2006; Khalil et al., 2009; Schwartz et al. 2001; Schwartz and Stewart 2007; Stewart and Schwartz 2007). The regression coefficients allow calculation of changes in higher-order "executive functions" involving decision-making and planning, and in motor co-ordination, and will be applied to estimate blood-lead effects in the present study.

1.5. Blood lead and the Franklin crew

No free blood has been recovered from the expedition's remains but D'Ortenzio et al. (2018) have estimated blood lead from the hair of an officer which describes his exposure over three months prior to death. The skeletal remains were discovered on the south-east coast of King William Island and have been identified as most probably those of Harry Goodsir who was assistant surgeon on HMS *Erebus* (see Mays et al., 2011; Stenton, 2018).

Goodsir's skeleton bore no evidence of scurvy or tubercular disease; an infection in the maxilla may have contributed to his death (Mays et al., 2011). The careful construction of his grave has been interpreted as evidence that Goodsir may have died before the desertion of the ships in April 1848, perhaps during a sledging mission while normal order was maintained. During the retreat that followed the final desertion of the ships, bodies were commonly left where they fell (D'Ortenzio et al., 2018).

Goodsir's blood lead was estimated from scalp hairs adhering to clothing in the grave. Lead in blood becomes bound in the hair root where its concentration reflects current exposure (Clarkson and Magos, 2006). Hair grows at approximately 1cm per month so that the 3cm sample indicated blood lead of 61.3 µgPb/dl at 3 months prior to death (the distal end of the sample), decreasing to 53.6 µgPb/dl (at the root) some weeks before death. The small reduction in blood lead over the period may be due to Goodsir having been away from the relatively contaminated environment of the ships when he died (D'Ortenzio et al, 2018). Swanston et al. (2018) observe that exposure to lead was maintained during the expedition which, they point out, would be expected given the on-board sources of exposure.

The unique results of D'Ortenzio et al. (2018) allow the present study to estimate the effects of blood lead on Goodsir's mental function by applying the coefficients which define the relationship between blood lead and cognition described above. However, mental function is also affected by cumulative (i.e. long-term) exposure to lead which is estimated from the concentration of the metal in the tibia. Although the cumulative effect may be smaller relative to the immediate impact of blood lead in currently-exposed individuals (see Schwartz et al., 2001), it has functional significance due to its persistent and possibly progressive effect on cognition (Schwartz and Stewart, 2007). The authors are grateful to Professor B.S. Schwartz for advice as to the salience of both blood and tibia lead when estimating the effects on cognition (personal communication to KM, 14th June 2017).

It is then regrettable that Goodsir's levels of skeletal lead are unknown. Nonetheless, an estimate can be made of the cumulative effect of lead on Goodsir's cognitive function by considering his educational and professional achievement. Goodsir was of sufficient intellect

to qualify in medicine and have professional success before joining the Franklin expedition. His absolute lead exposure from childhood onwards cannot be known but all social classes in Victorian Britain were at risk of significant exposure throughout the lifespan. As such exposure is likely to have prevented the realisation of Goodsir's full cognitive potential (Lezak et al., 2012) then the implication is, first, that his adult cognitive function reflected the consequence of that exposure. Secondly, Goodsir's academic and professional success would imply that, despite that exposure, he achieved a level of function that was above average. Moreover, Goodsir's intellect, education and occupational attainment would have conferred a degree of "cognitive reserve" that afforded protection from lead and will have implications when interpreting the present results.

It will be shown below how definition of Goodsir's function as 'above average' allows his placement within the upper percentiles of scores on tests of neuropsychological function. From that placement, a quantitative estimate can be made of how his performance would decline as a function of his blood-lead concentrations using the regression coefficients described above.

2. Materials and Methods

2.1. Harry Goodsir

Henry ("Harry") Duncan Spens Goodsir was born in Fife, Scotland, on 3rd November 1819. In 1840 he attained the diploma *Licentiate of the Royal College of Surgeons of Edinburgh* (Royal College of Surgeons of Edinburgh, 1838) and subsequently practiced in anatomy, contributed to academic publications and was appointed Conservator to the Museum of the Royal College of Surgeons of Edinburgh (Kaufman, 2004). He was appointed as naturalist and assistant surgeon to the Franklin expedition in 1845 and is supposed to have died in 1847 or 1848 at around 28 years of age.

2.2 Data sources

The estimates of Goodsir's blood lead by D'Ortenzio et al. (2018) are shown in Table 1a. Regression coefficients which define the relationship between blood lead and neuropsychological performance are derived from the study of an occupationally-exposed

cohort and control group (N = 803 and 135, respectively) by Schwartz et al. (2001) to determine the effects of lead upon cognitive function (see Schwartz and Stewart, 2007; Stewart and Schwartz, 2007). The coefficients are shown in Table 1b and described further below.

2.3. Neuropsychological assessment

Four neuropsychological tests shown sensitive to blood lead were selected from the battery applied by Schwartz et al. (2001). Full description of the tests is given in Appendix A. Tests of higher order "executive functions" involving decision-making, attention, visual scanning and memory were represented by the Digit symbol substitution test (hereafter, Digit symbol test) and the Trail-making Test-B (Trails-B test). Psychomotor performance was represented by the Pegboard test (Lafayette Instrument, 2015) requiring manual dexterity and fine motor control, and the Pursuit aiming test requiring accurate eye-hand co-ordination. The tests have wide use in clinical practice (Lezak., et al., 2012; Mitrushina et al., 2005; Strauss et al., 2006). The Digit symbol and Trails-B tests are sensitive to the benefits of cognitive reserve in lead-exposed individuals (Bleecker et al., 2007).

2.4 Estimation of effects of lead on cognition

The analysis by Schwartz et al. (2001) applied four regression models which examined the effects on neuropsychological test scores of blood lead and tibia lead either separately or together, and with or without the covariate of job duration (other covariates including age, education and life-style habits were applied in all models). Model 3 was selected for present purposes because it involved blood lead alone (Goodsir's tibia lead being unknown) and job duration which reflects cumulative exposure to lead. The regression coefficients defined the degree of change in a given neuropsychological score as a function of an increase of 1μgPb/dl blood (Table 1).

The effects of blood lead were determined by multiplying the regression coefficient for a given test by the values of lead shown in Table 1a and b. For clarity, the figures show the products only for Goodsir's lowest and highest blood-lead concentrations of 53.6 and 61.3 μg/Pb dl, respectively. Confidence intervals derived from the standard error (SE) of

each coefficient are also shown. Note that it is only the particular contribution of lead to cognitive performance which is considered. The uncertainties associated with the contribution of other factors are discussed below through the proposals for a reference point on the performance scales from which cognitive deficits due to lead may be assessed.

2.5. Defining cognitive impairment

A commonly-applied criterion of impairment is where an individual's score on a neuropsychological test falls more than one standard deviation (1 SD) below the mean of a normative group's performance. However, it is more satisfactory diagnostically to have an estimate of the individual's "pre-morbid" function from which to subtract their test score rather than simply compare it to a norm. For example, a test score at the 50th percentile would be classed as "average" and not indicative of impairment: but if the pre-morbid level of performance was known to have been at the 80th percentile then the decline would be of clinical interest (see Lezak et al., 2012). In the case of Goodsir, it is possible to establish an estimate of pre-morbid function as follows.

As discussed, Goodsir's level of cognitive function is concluded to have been above average and to be the resultant of his cumulative exposure to lead. This level will define his "pre-morbid" performance from which the acute effects of his current blood lead will be subtracted. Distributions of neuropsychological test scores can be categorised into percentile ranges to denote performance ranging from "superior" to "impaired" (see below). Scores within the 75th to 90th percentile range are defined as "high average" (25th to 74th percentiles denote "average" performance). As Goodsir's cognitive function is assumed above average, it is proposed reasonable to locate his pre-morbid performance around the mid-point of the "high average" range: the 84th percentile is 1 SD above the mean of a distribution and is chosen, somewhat arbitrarily, as his cognitive level.

The percentile distributions of test scores from the control group of Schwartz et al. (2001, their Table 4) will be presented in the figures. They will include Goodsir's pre-morbid level of performance at the 84th percentile with the estimated deficit due to his blood lead shown as a decline in percentile points from that level.

3. Results

The effects of Goodsir's blood-lead concentrations upon the performance of the four neuropsychological tests are shown in Figure 1.

3.1 Executive function

3.1.1. Digit symbol test: In Panel A the lead-related deficit in performance (number of correct responses) is shown from a zero baseline which denotes the pre-morbid level of performance expected if there were no current acute exposure to lead. The regression line shows the mean deficit in performance expected across a blood-lead range of 40 to 70 µgPb/dl which encompasses Goodsir's blood-lead levels. A confidence interval (CI) for the size of the mean deficit is shown by the shaded area around the regression line and illustrates the potential range of values that the true mean might take. As the lower limit of the CI would have exceeded zero, it is truncated at the zero baseline (if the CI extended above the baseline it would imply an improvement in performance due to lead which is biologically implausible). The performance deficits associated with Goodsir's blood levels of 53.6 and 61.3 µg/Pb dl are shown by the vertical blue and red bars, respectively. The difference in mean deficit between the two blood levels is only 0.5 of a score point and would be of no functional significance. Goodsir's higher blood level is associated with a mean score deficit of 2.7 which the CI shows might range from 0 to 6.0 points.

Panel B shows the distribution of Digit symbol scores from the control group of Schwartz et al. (2001). The shaded areas of the distribution show the following percentile ranges which denote from left to right, respectively, "impaired/low average" (0-24th percentile), "average" (25-74th), "high average" (75-90th) and "superior" (91st – 100th) performance, after Mitrushina et al. (2005). The blue and red bars show Goodsir's deficit score ranges transposed from Panel A so that they have their origin at the 84th percentile denoting his pre-morbid level of performance. The CI associated with his higher blood-lead level (red bar) extends leftwards from the 84th percentile where the extreme 6.0-point estimate of the test-score deficit falls only marginally within the very upper percentiles of the "average" category. If the mean deficit of 2.7 shown in Panel A is a reliable summary score,

then Goodsir's performance would remain within the "high average" category. In the case of Goodsir's lower blood level (blue bar), his performance remains within the "above average" category across the estimated deficit range.

3.1.2. Trail making test-B: Panels A and B present the association between Goodsir's blood lead and performance in an identical manner to that for the Digit symbol test. However, it is important to note that the coefficients describing the effects of lead on Trails-B performance (time to complete the test) were derived from $\log_e$ transformed data which was necessary to normalise the positively-skewed distribution of raw scores (see Schwartz et al., 2001). The deficit scores shown in Panel A are therefore the products of $\log_e$-derived coefficients and Goodsir's blood-lead levels. The blue and red bars again show the performance deficits associated with Goodsir's blood lead. The thin upper sections of the bars indicate the plausible minimum size of the mean deficit, corresponding to the lower end of the CI. The thicker section of the bar corresponds to mean deficits which lie inside the confidence interval. As in the case of Digit symbol performance, the difference in mean deficit between the two blood levels is very small.

As the lead-related performance deficits are based upon $\log_e$-derived coefficients, the distribution of the control group scores shown in Panel B has been adapted appropriately as follows. If the mean and standard deviation of the Trails-B score distribution on its observed raw-score scale (X) are m_x and σ_X respectively, then under the assumption of a log-normal distribution, the mean and standard deviation of the distribution on the log scale (Y) are

$$m_y = 2 \log (m_x) - \tfrac{1}{2}\log (m^2_x + \sigma^2_x)$$

$$\sigma_y = \sqrt{-2 \log (m_x) + \log (m^2_x + \sigma^2_x)}$$

and the resultant distribution is shown in Panel B.

As was seen in Digit symbol performance, it is evident that only in the case of the most extreme deficit estimated by the CI for the higher blood lead level (red bar) does performance fall marginally from "high average" into the upper percentile range of the

"average" category. The mean decline corresponds to values well within the high average percentile range and would not suggest impairment.

3.2. Psychomotor function

The deficits associated with Goodsir's blood lead and performance of the Pegboard and Pursuit Aiming tests (scores being the number of correct responses) are shown in Panel A of the respective plots where, as before, only marginally greater deficit is seen for the higher blood-lead level. Panel B of both tests shows that performance declines from "above average" to near the mid-point of the "average" category. It is therefore evident that a greater deficit is associated with the tests of psychomotor function than with those of executive function and the extent to which such decline might indicate impairment is discussed below.

4. Discussion

The results estimate the effects of Goodsir's blood lead concentrations on his neuropsychological function. Whilst it is unknown how Victorians might have performed on these tests, there is no reason to suppose that their performance would have been inferior (see Woodley et al., 2013). However, because the data are derived from a present-day cohort, their strict interpretation is that they represent how a present-day individual of "high average" cognitive function might perform with the same blood-lead level as Goodsir. With this *caveat* in mind, the mean deficit in "executive" performance associated with Goodsir's blood lead would remain within the "high average" percentile range. Even if the most extreme deficit were applied as estimated from the confidence intervals around the means of the Digit symbol and Trails-B test, Goodsir's performance would fall within the upper percentiles of "average" performance. Such outcomes would not imply an adverse functional consequence.

The supposition that Goodsir had above average cognitive function and the evidence that such status confers "cognitive reserve" which affords protection from the adverse effects of lead may imply that the results over-estimate the effects of lead upon his executive function. The coefficients describing the association between blood lead and Digit symbol

and Trails-B performance in lead-exposed workers with cognitive reserve are 60% and 64% smaller in magnitude, respectively, than workers who lack reserve (Bleecker et al., 2007). If such a reduction were applied to the present coefficients then the effects of lead would be extremely small. However, Schwartz et al. (2001) adjusted for education as a covariate in their analysis which therefore takes account of one factor that would contribute to Goodsir's cognitive reserve (the others being childhood intellectual ability and occupational achievement for which no adjustments were made). Therefore, it cannot be concluded that Goodsir's cognitive reserve might have reduced the magnitude of the presently-applied coefficients to the extent observed by Bleecker et al. (2007) but the potential to reduce the degree of deficit should be recognised.

It should be emphasised that the conclusion is *not* that Goodsir's mental function was unaffected by lead. On the contrary, all the evidence for the adverse effects of lead on cognition, and the widespread exposure of the Victorian population, suggest that, for many, it would have been inevitable to a lesser or greater degree. Rather, the conclusion is that the effects estimated here would have had no functional consequence for the performance of Goodsir's duties that relied upon higher-order cognitive processes.

Lead exerts a greater influence on psychomotor performance (Schwartz et al., 2001; Stollery et al., 1991) and, when the metal has affected the basal ganglia of the brain, performance will often fall within the lowest percentiles (Bowler and Lezak, 2015). Goodsir's' blood-lead concentrations were associated with deficits in Pegboard and Pursuit aiming performance to a level that might approach the mid-point of the "average" range. Although the latter does not imply impairment in absolute terms, it would mark a decline from Goodsir's assumed "high average" pre-morbid level of psychomotor performance (his practice in anatomy would require eye-hand co-ordination and fine motor control). This deficit in eye-hand co-ordination and dexterity might have affected accuracy when hunting with firearms and thus had implications for maintaining food stocks although it is perhaps unlikely that a poor marksman would have been assigned to such duty in the first place. The fact that Goodsir is assumed to have died while on a mission away from the ships while

normal order prevailed (D'Ortenzio et al., 2018, above) would imply that his blood-lead concentrations had not impaired his mental or physical capacity in any obvious way and that he was deemed fit for duty.

Whilst the principal concern is Goodsir's cognitive function, it is important to consider the potential effects of blood-lead upon his physical health which might also have impaired his effectiveness as an officer. Goodsir's blood-lead concentrations of 56.3 to 61.3 μgPb/dl fall within the range where clinical symptoms may not always be evident (Needleman, 2004) and are below the maxima reported in some present-day, lead-exposed workers: for example 88.2 μgPb/dl (Grandjean et al., 1978), 89.3 μgPb/dl (Dorsey et al., 2006) and 76 μgPb/dl (Schwartz et al., 2005). However, the marked inter-individual variation in sensitivity to lead means that it is possible that Goodsir experienced minor, non-specific symptoms including dyspepsia and headache (Kosnett et al., 2007). It has been suggested that little was known of lead intoxication in the nineteenth century and that the expedition's surgeons would have found it difficult to diagnose the condition (Wilson, 2004), but the opposite was true. Victorian physicians and Royal Naval surgeons understood very well the signs and symptoms of lead poisoning which they encountered during training and in practice (Harrison, 1852; *London Medical Gazette*, 1836; Turnbull, 1806). Misdiagnosis was a possibility, however, when mild symptoms mimicked those of other common ailments (Harrison, 1852), but it can only be conjecture whether Goodsir exhibited such symptoms and, far less, whether they led to misdiagnosis. The matter is important in the context of the misdiagnosis of other significant conditions that affected polar expeditions of the nineteenth and early twentieth centuries due to imperfect understanding of their causes, signs and symptoms (see Guly, 2012, 2013).

Several factors require caution when interpreting the present results. First, the assumption that Goodsir was of above average intellect is critical because it determined his placing within the "high average" percentile range which meant that the estimated deficits in his executive performance remained largely within that category. Goodsir's training and professional practice support the assumption of above-average intellect, but patronage could

facilitate the medical careers of less intellectually-gifted individuals in Victorian times (McLean, 2010) and Goodsir's grandfather, father, uncles and brothers constituted "a famous line of doctors" of some influence (Kaufman, 2004). However, the Royal Navy was fortunate that the Physician-General Sir William Burnett M.D. had a reputation for upholding the Admiralty's standards for entry to its medical service and, indeed, was sympathetic to men of ability from humble backgrounds (McLean, 2010). Charles Darwin did facilitate Goodsir's introduction to the expedition through their shared interest in barnacles (Lambert, 2009), with the botanist Joseph Hooker acting as intermediary having served as assistant surgeon with the expedition's second-in-command, Francis Crozier, on an earlier Antarctic mission (Palin, 2018). Whist this introduction was no doubt helpful, there is no evidence that Goodsir's professional achievements or interest in barnacles reflected anything other than his own medical and scientific ability and that he was, independently, of relatively higher intellectual function.

Secondly, although the results provide insight to the effects of lead upon Goodsir's mental function, they reflect only the acute effects of blood-borne lead. As explained above, lead in the tibia is a marker of cumulative exposure which may exert a persistent adverse effect (Schwartz et al., 2005; Schwartz and Stewart, 2007; Shih et al., 2007; Stewart and Schwartz, 2007). Had Goodsir's tibia lead been known it would have allowed estimation of cognitive effects of his early (pre-expedition) exposure although the present study has attempted to account for this effect when estimating his pre-morbid level of function. Given Goodsir's age at death, his cumulative exposure may have made a relatively minor contribution to the deficits associated with his blood-lead, as seen in the marginal plots of cognitive performance as a function of tibia lead and job duration (exposure) of Schwartz et al. (2001). Age is itself associated with cognitive decline and adjustment was made for the factor by Schwartz et al. (2001).

Thirdly, present-day, lead-exposed groups are only partial proxies for the Franklin crew, many of whom are assumed to have had life-long exposure to lead. Whilst present-day groups have similar skeletal burdens to those of the crew, their exposure duration has

been shorter and is unlikely to have been significant *in utero* and childhood when lead is particularly harmful. The effects of lead reflected in the coefficients may therefore underestimate those that might characterise a Victorian sample. Moreover, the present-day cohort was adequately nourished and performed the cognitive tests in a benign environment. In contrast, the Franklin crew faced nutritional deficiencies (Park and Stenton, 2019) and physical and mental stress that would have increased after the desertion of the ships. Deficiencies including those of vitamin C and iron influence gastric absorption of lead while stress stimulates the hypothalamic-pituitary axis to release cortisol and associated mobilisation of lead from bone into the blood (Cheng et al., 1998; Peters et al., 2010). It was noted that Goodsir may have died before the desertion of the ships and therefore at a time when such conditions may have had relatively little influence. The same might not be true of those officers who remained in command after the desertion although the impact on their decision-making and judgement, if any, cannot be known.

A further issue concerns the relative insensitivity of neuropsychological tests seen in the overlap in performance of lead-exposed and non-exposed groups (e.g. Baker et al., 1984; Grandjean et al., 1984; Schwartz et al., 2001; Stewart et al., 1999; Weisskopf et al., 2004) and the clinical observation that some 15% of cognitively- and neurologically-intact individuals may score below the 1 SD cut-off that implies impairment (e.g. Lezak et al., 2012). Consequently, Stewart and Schwartz (2007) advocate MRI and other imaging procedures to examine lead-related structural changes in brain areas with known functional relationships (Caffo et al., 2008; Hsieh et al., 2009; Sindhu and Sutherling, 2015; Stewart et al., 2006; Tüzün et al., 2002). Goodsir's remains allow no such insight but *post mortem* examinations of the permafrost-preserved bodies of the men who died at Beechey Island included X-ray imaging of the brain. The brain of John Torrington (leading stoker, HMS *Terror*) was found to be autolysed (Amy et al., 1986) but some structures in the brains of John Hartnell and William Braine (able seaman and Royal Marine, respectively, HMS *Erebus*) were preserved and no calcification of the basal ganglia was evident (Notman and

Beattie, 1995; Notman et al., 1987), the latter being a recognised, although not inevitable, sign of chronic lead exposure.

Finally, the present analysis is a single-case study so that the effects of lead adduced for Goodsir may not be representative of other officers. Despite this limitation, several single-case and small-sample studies have determined whether conditions including scurvy, tuberculosis, lead exposure and nutritional status affected the physical health of the Franklin crew (e.g. Beattie, 1985; Christensen et al., 2017; D'Ortenzio et al., 2018; Forst and Brown, 2017; Kowal et al., 1989, 1991; Mays et al., 2011, 2013; Swanston et al., 2018). The present study may contribute to those insights by estimating how lead might have affected mental function. This approach may be coined 'cognitive archaeology' and might be applied to human remains from other eras where there was exposure to lead and other heavy metals known to affect cognition.

5. Conclusion

The present results may contribute to the understanding of factors that affected the health of the Franklin expedition by providing a cautious insight to mental function. The estimated changes in cognition associated with the blood-lead levels of an officer who probably died before or around the time of desertion of the ships would be unlikely to have had a significant impact upon his higher-order cognitive performance. His psychomotor function would have suffered greater deficit but would not be termed as formal impairment. As in the case of all research concerning the health of the expedition these conclusions must be guarded in the absence of documentary evidence from the logs and medical records of the expedition itself. Those journals were supposed to be irretrievably lost (Cyriax, 1969) but there is now the prospect that some may be found preserved on the recently discovered ships (Harris, 2014; Woodman, 2015 p268). Only those records would provide reliable evidence of the physical and mental status of the officers and men.

Author contributions

KM is the corresponding author and devised the study. AWB devised and conducted the analysis. Both authors drafted the manuscript and conclusions.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A

Description of neuropsychological tests

The Digit symbol substitution test (hereafter, Digit symbol test) and Trail-making test B (Trails-B test) are paper-and pencil-administered tests although computerised variants are available. Both are tests of higher-order "executive" function requiring speeded decision-making, attention, mental flexibility, visual scanning and working memory.

Digit symbol test: the subject is presented with a coding key showing the digits 1 to 9, each paired with a simple symbol; e.g. 2 with Ⱶ , 9 with □ , 5 with ∆ etc. Below the coding key, the digits are presented randomly in rows, each with an accompanying response box. Working as quickly as possible, the subject must enter the correct symbol for each digit in the box. The score is the number of correctly inserted symbols within a given time (e.g. 90s). The test assesses visual attention and scanning, memory and speeded motor response.

Trails-B test: the capitalised letters of the alphabet (excluding the letter I) and the digits 1 to 25 are presented, scattered randomly across a sheet of paper. The subject uses a pencil to draw a continuous connection between the stimuli according to the following alternating sequence: 1 to A to 2 to B to 3 to C and so on. The score is the time taken (s) to complete

the test which assesses visual search and scanning, attention switching and speed of mental processing.

The Purdue Pegboard assembly test (Pegboard test) and the Pursuit aiming test assess psychomotor functions including eye-hand co-ordination, dexterity and fine motor control.

Pegboard test: the assembly test presents the subject with a commercially-manufactured pegboard, pins for insertion in the board, and washers to be inserted over the pins (Lafayette Instrument, 2015). The test involves picking up a pin with the fingers of one hand and, while inserting the pin in the board, picking up a washer with the other hand and placing it over the inserted pin while the first hand selects a further pin and so the test continues as a continuous series of co-ordinated actions. The subject must work as quickly as possible: the score is the number of assemblies completed in 60s. The test assesses eye-hand co-ordination, motor sequencing, fine motor control and dexterity.

Pursuit aiming test: the test presents numerous small circles scattered across a sheet of paper. Using a pencil and working as quickly as possible, the subject must mark a dot accurately in the centre of each circle. The score is the number of dots placed accurately within a given time, e.g. 60s. The test requires accurate eye-hand co-ordination, fine motor control and sustained attention.

Table 1. Data sources. (a) Blood-lead concentrations in the hair of Harry Goodsir at three time-points prior to his death (D'Ortenzio et al., 2018, Table 1). (b) Regression coefficients and associated standard errors describing the relationship between blood lead concentration and neuropsychological test performance and peripheral nervous system motor strength (Schwartz et al., 2001, Table 5). *Coefficient derived from $\log_e$ transformed data.

a) Blood lead

	Months prior to death		
	3 months	**2 months**	**1 month**
Blood lead (µgPb/dl)	61.3	54.6	53.6

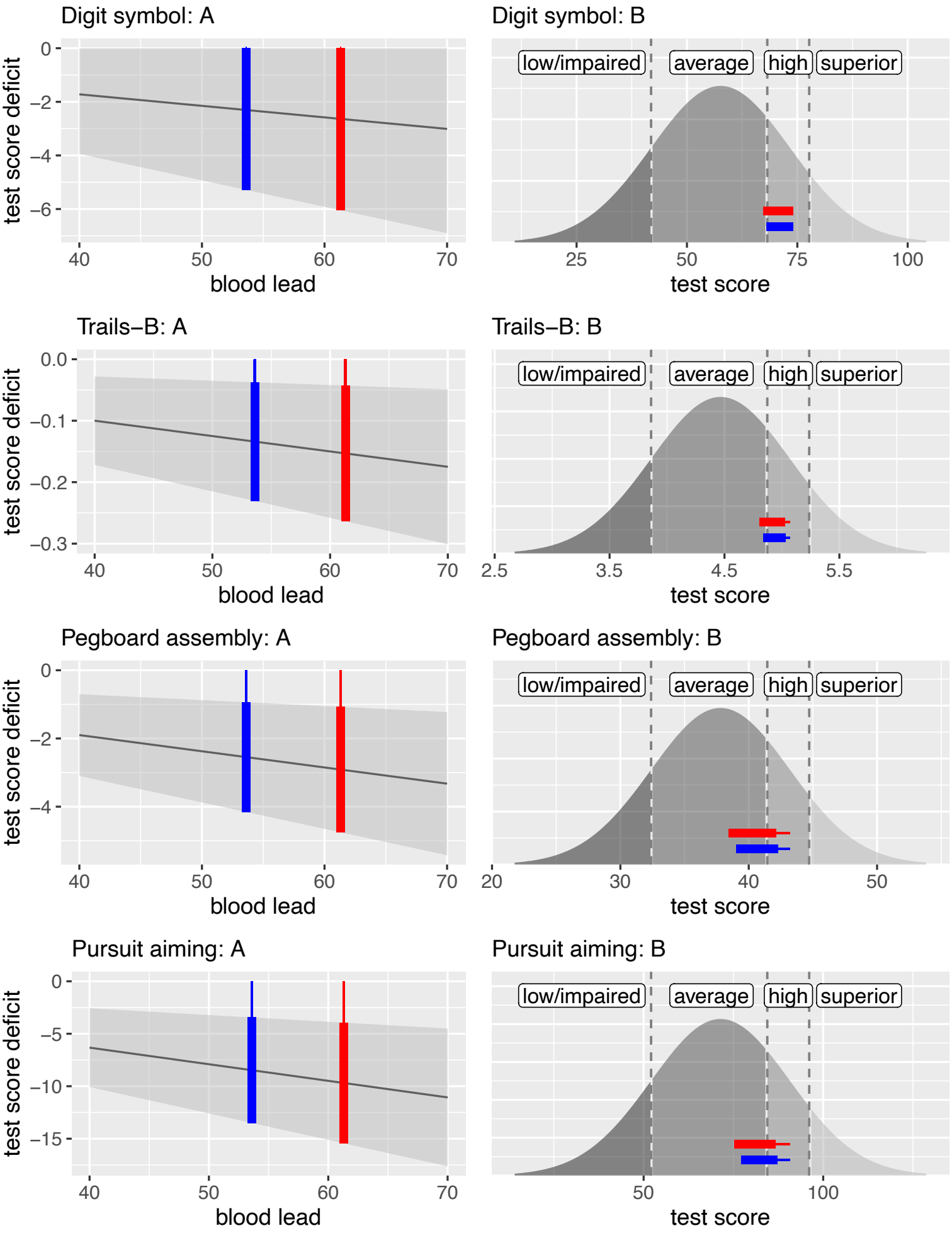
b) Regression coefficients

	Regression coefficient (standard error)	
Executive function	**Trail B test***	**Digit-symbol test**
	-0.0025 (0.0009)	-0.0430 (0.0278)
Psychomotor function	**Pegboard assembly**	**Pursuit aiming**
	-0.0475 (0.0150)	-0.1581 (0.0469)

Figure caption

Figure 1. Estimation of the effects of two levels of blood lead from an officer of the Franklin expedition on the performance of four neuropsychological tests. Panel A in each figure shows the estimated deficit in performance from a zero baseline indicating the pre-morbid state. Panel B of each figure shows the deficit in the context of the percentile ranges that classify the level of neuropsychological performance. The pre-morbid level of function is set at the 84^{th} percentile.

(Note: the Figure will require 2 column widths)


Digit symbol: A
test score deficit
0
−2
−4
−6
40
50
60
70
blood lead
Digit symbol: B
low/impaired
average
high
superior
25
50
75
100
test score
Trails−B: A
test score deficit
0.0
−0.1
−0.2
−0.3
40
50
60
70
blood lead
Trails−B: B
low/impaired
average
high
superior
2.5
3.5
4.5
5.5
test score
Pegboard assembly: A
test score deficit
0
−2
−4
40
50
60
70
blood lead
Pegboard assembly: B
low/impaired
average
high
superior
20
30
40
50
test score
Pursuit aiming: A
test score deficit
0
−5
−10
−15
40
50
60
70
blood lead
Pursuit aiming: B
low/impaired
average
high
superior
50
100
test score