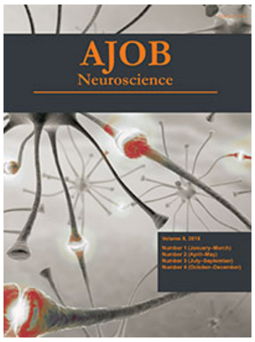

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The Impact of a Landmark Neuroscience Study on Free Will: A Qualitative Analysis of Articles Using Libet and Colleagues' Methods

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Target Article

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The Impact of a Landmark Neuroscience Study on Free Will: A Qualitative Analysis of Articles Using Libet and Colleagues' Methods

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Gathering evidence across disciplines is a strength of interdisciplinary fields like neuroethics. However, conclusions can only be made if the evidence applies to the issue at hand. Libet and colleagues' 1983 experiment is an interesting case study in this problem. Despite ongoing critiques about the methods used and the replicability of its findings, many people consider Libet and colleagues' methodology a valid strategy to investigate free will and related topics. We reviewed studies using methods similar to those of Libet and colleagues ($N = 48$) to identify its use and the evidence produced. Overall, we found substantial variation between studies. While the Libet paradigm may be useful for examining how stimuli affect temporal judgments, the link between this and free will or moral responsibility is not clear. Being aware and critical of the methods used to gather results is important when applying scientific experiments to complex, abstract phenomena.

Keywords: Libet, free will, intentional binding, voluntary action, review

One of the goals of neuroethics is to see whether insights from neuroscience can be used to inform philosophical concepts related to the self (Racine et al. 2017). One landmark experiment in the field was conducted by Libet and colleagues in the early 1980s. This experiment has been credited as one of the first experimental techniques to investigate "free will" (Jasper 1985; Ringo 1985; Schlosser 2014). Libet and colleagues (1983) recorded neural activity several hundred milliseconds before participants reported being aware of their intention to act (see Box 1). While some scholars feel that these findings refute or place limitations on the existence of free will, this study's significance continues to be debated (see, e.g., Anonymous 2013; Klemm 2010; Mele 2006; Radder and Meynen 2013; Roskies 2010; Schlosser 2014). Support for the relevance of Libet and colleagues' (1983) findings to the debate about free will rests on the assumption that the methods target the underlying neural mechanisms of free will, rather than some other phenomena. In fact, leading researchers in the "neuroscience of free will" consider the Libet and colleagues paradigm to offer "one of the few viable methods for experimental studies of awareness of action" (Haggard 2005).

Although the debate about Libet and colleagues' method has raged for decades, we were unable to find a review of articles using their methods. Therefore, we conducted a review of articles using Libet and colleagues' (1983) methods to summarize the data they have produced and to identify whether the method has been replicated.

METHODS

Search Strategy

We conducted a review of articles that cited Libet et al. (1983) and decided to expand it to include Soon et al.

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Supplemental data for this article can be accessed on the publisher's website.

BOX 1: OVERVIEW OF LIBET AND COLLEAGUES' 1983 EXPERIMENT

In the original experiment, participants monitored by an electroencephalogram (EEG) were asked to make a "quick, abrupt flexion of the fingers and/or the wrist of [their] right hand" without preplanning their action (Libet et al. 1983) and then report the position of a rotating spot of light on a clock face (1 revolution = 2.56 sec) when they first became aware (a) of their "wanting" to perform the movement (W) OR (b) that they had actually moved (M). The mean values for W and M were 200 msec and 85 msec before movement, respectively. W was also reported as 150 msec after subtracting a measure of participants' subjective biases (S). Researchers compared these measurements to neural signals ("readiness potentials" [RP]) recorded by EEG. On average, RP measurements preceded W measurements by about 350 msec. From this, Libet and colleagues concluded that the initiation of voluntary action begins before an individual makes a conscious decision to act (Libet et al. 1983). They also speculated that the gap between W and movement initiation could allow some "conscious veto power" to abort the unconsciously decided movement. Libet and colleagues (1983) hypothesized that this veto power would preserve an individual's conscious and voluntary control over their actions. Libet himself stated that "in those voluntary actions . . . in which conscious deliberation (of whether to act or of what alternative choice to take) precedes the act, the possibilities for conscious initiation and control would not be excluded by the present evidence" (Libet et al. 1983), and, separately, that "what we have achieved experimentally is some knowledge of how *free will* may operate but we have not answered the question of whether our consciously willed acts are fully determined by natural laws that govern the activities of nerve cells in the brain, or whether acts and the conscious decisions to perform them can proceed to some degree independently of natural determinism" (Libet 2010).

(2008) and Libet (1985) (Web of Science, June 10, 2013, $N = 323$) once we realized that one paper we had identified in preliminary searches (Soon et al. 2008) did not cite the 1983 paper. We included articles published in English, and no duplicates were identified by Scopus Direct or Web of Science. Database searches yielded an initial sample of 801 articles: (1) Libet et al. (1983) (Scopus Direct, June 4, 2013, $N = 300$); (2) Soon et al. (2008) (Scopus Direct, June 10, 2013, $N = 178$); and (3) Libet (1985) (Web of Science, June 10, 2013, $N = 323$). We identified 21 duplicates, which were excluded. We reviewed all remaining abstracts.

Abstract Screening

We included articles if they used methods similar to those of Libet and colleagues (1983), focused on free will or similar terms (e.g., voluntary action, intention, volition, intentional action), or mentioned the implications of Libet and colleagues' (1983) experiment on free will. We only included articles that reported original research (e.g., we excluded reviews). Articles were excluded if they did not focus on free will. After applying the inclusion and exclusion criteria, we identified 56 unique articles that used a method similar to Libet and colleagues (1983) ($N = 57$ including Libet and colleagues' 1983 experiment).

Full-Text Screening

Due to the significant variability in methods we observed at the full-text screening phase, we decided to define the Libet paradigm to facilitate analysis. We defined key features of the "Libet Paradigm" (see Box 2) by analyzing the sample and noting the features that were present in the majority of the articles and also in Libet and colleagues' paper. Since very few papers included all of these components, scientific articles on free will using Libet-like methods were excluded if they did not meet three of the five criteria. We excluded 17 articles that made it through abstract screening on this basis. This entire search was repeated on October 3, 2014, to capture all articles published between January 1, 2013, and October 2, 2014. This secondary search yielded 226 additional articles. Of these, eight were ultimately included in our sample (final $N = 48$, including Libet et al. 1983) (see Figure 1 and Supplementary Table 1).

Data Extraction

We created a coding guide based on an initial pilot sample ($N = 8$: Fried, Mukamel, and Kreiman 2011; Haggard, Clark, and Kalogeras 2002; Haggard and Eimer 1999; Keller and Heckhausen 1990; Lau et al. 2004; Libet et al. 1983; Sirigu et al. 2004; Soon et al. 2008) to facilitate content analysis. Two reviewers independently coded 10% of the entire sample using this guide to check interrater reliability and reduce bias (four articles: Haggard et al. 2003; Miller, Shepherdson, and Trevena 2011; Moore et al. 2010; Pockett and Miller 2007). We discussed any differences in coding and revised the coding strategy before proceeding further. We captured information about (1) the methods used in each paper (number of participants, groups, type of recordings, neural origins of the results) and (2) the results reported (timing of W, M, RP, and related measurements, neural correlates reported by authors). Due to the extensive variation in the methods that were used across the articles, only information that could be compared with the Libet and colleagues (1983) paper was extracted.[1]

1. For example, any measurements that various articles reported about when participants perceived the occurrence of an auditory tone were not included here because Libet et al. (1983) did not include auditory stimuli.

LIBET PARADIGM

1. Participants were instructed to look at a visual stimulus that was used to measure the time of an action or intention.
2. Subjects indicated an action or intention by identifying the position of an object (e.g., letter, spot of light on a clock face). If a clock was used, two of the following had to be met:
   a. each revolution took 2.56 sec,
   b. the face had markings that corresponded to five minute intervals on a standard clock,
   c. subjects were instructed to wait for one revolution before acting.
3. Participants were instructed to make a spontaneous, voluntary movement at a time of their choosing. It was specified that this movement could not be premeditated.
4. W (awareness of "wanting" to perform an action) or M (subject's awareness that they had actually moved) was measured over the course of the experiment.
5. In each experimental condition, at least 40 trials had to be performed to obtain the final measurement (excludes training trials).

Box 2: The Libet Paradigm. The five items included are aspects of Libet and colleagues' method that were the most frequently replicated across the article in our primary sample ($N = 57$). Three of five had to be present for an article to be included. The items were chosen to facilitate comparisons between similar articles.

RESULTS

To facilitate the analysis of the results, our findings are grouped into two broad categories: (1) information about the methods used, and (2) evidence produced by these experiments. All analyses exclude Libet et al. (1983) ($N = 47$) unless otherwise stated.

Methods Used in the Sample

Methodological Variation

Within our sample, a majority of articles identified Libet et al. (1983) as the single source for their methods (Table 1). More precise details about each of the articles included, as well as how they satisfied the requirements of the paradigm, can be found in Supplemental Tables 1 and 2.

We categorized the articles depending on how they differed from the original paradigm used by Libet et al. (1983) to capture the variety of methods used (see Table 2). Five groups of articles were identified. There was considerable variation in the aspects being measured and the components of the paradigm that were included.

Population Type (Includes Libet et al. 1983)

Almost all studies recruited participants with no stated medical conditions (47/48; 97.9%). Of these, 37/47 (78.7%) exclusively recruited these populations and 10/47 (21.3%) compared the results from these populations to other groups. These other groups consisted of individuals with extensive meditation experience ($n = 2$), and individuals from various patient groups (those with brain lesions, $n = 2$; psychogenic tremor, $n = 1$; Gilles de la Tourette's, $n = 1$; deafferented neurons below the neck, $n = 1$; schizophrenia, $n = 1$; Parkinson's disease, $n = 1$; and conversion disorder, $n = 1$). One study only recruited epileptic patients and did not compare them to a control group (1/48; 2.1%).

Technique Used (Includes Libet et al. 1983)

Thirty of 48 (62.5%) articles used a recording technique to obtain their measurements; 18/48 (37.5%) relied on participant self-reports. Electroencephalogram (EEG) was the most prevalent technique used (19/30; 63.3%), followed by functional magnetic resonance imaging (fMRI) (7/30; 23.3%), transcranial magnetic stimulation (TMS) (2/30; 6.7%),[2] depth electrodes (1/30; 3.3%) and exclusively electromyography (EMG)[3] (1/30; 3.3%). Only 4/11 studies that recruited specific populations used a recording technique. The rest used self-report measures. Conversely, 29/47 (61.7%) studies that used healthy individuals did use a recording technique.

Timing Reported in Each Study

The point at which data recording began (0 msec) varied between articles. Articles defined the starting point as the first sign of EMG activity, at the moment when a key, button, or lever was pushed (as applicable), and many experiments did not explicitly define their starting point. We analyzed all measurements together regardless of the starting point. Analyses were conducted using average values only as standard deviations were not provided for all studies.

Average W Times (msec; Includes Libet et al. 1983)

W corresponds to participants' first awareness of their intention to act (Libet et al. 1983). In total, 27/48 (56.3%) articles measured W (see Figure 2). Three studies (four conditions) only provided average values in accompanying figures or tables (Edwards et al. 2011; Keller and Heckhausen 1990; Lafargue and Duffau 2008). Three articles measured W but did not report the average value either in figures or in text. Two of these provided a range

2. TMS is a noninvasive stimulation technique, not a recording technique. However, as data about the timing and location of the stimulation were obtained through the use of TMS we have categorized articles using this methodology as using a recording technique. The participants' reported measurements for these articles are based on self-report.

3. It should be noted that most EEG experiments also used EMG, but only one experiment used EMG without EEG.

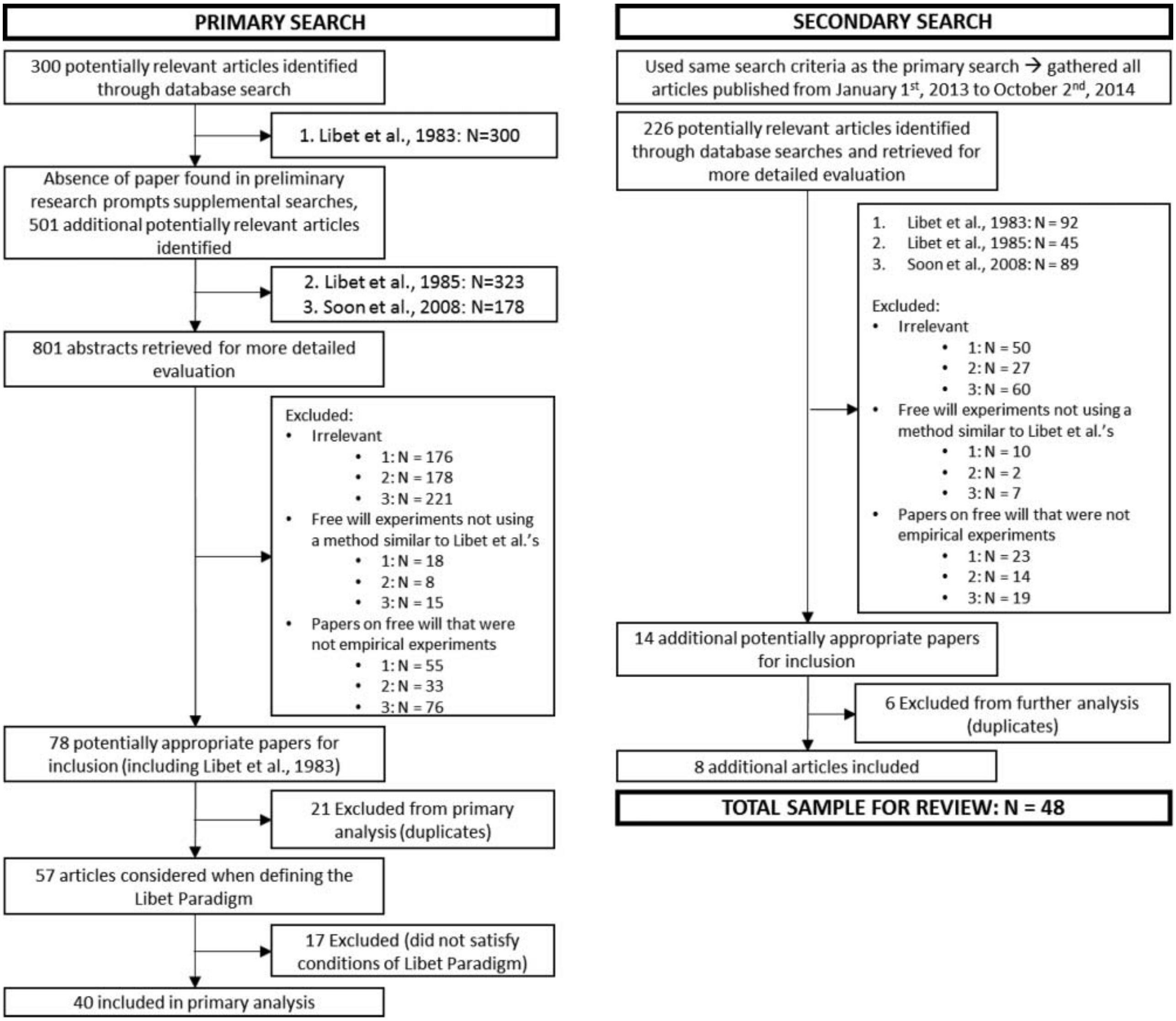

Figure 1. Sampling method for finding articles containing a paradigm similar to Libet and colleagues' (1983) article.

of measurements W fell within (Bode et al. 2011; Soon et al. 2008), while the remaining study did not provide any sort of W measurement (Soon et al. 2013).

Five articles (13/57 conditions) reported an average W value between 0 and 99 msec before action, while 11 (17/57 conditions) reported those 100–199 msec before action, 12/57 (21.1%, 9 unique studies) fell 200–299 msec before action, 5/57 (8.8%, 4 unique studies) had values between 300 and 399 msec before action, 3/57 (5.3%, 2 unique studies) found W that occurred after the time of action, 3/57 (5.3%, 2 unique studies) had values between 400 and 499 msec before action, and only one condition (1.8%, 1 unique study) yielded an average W between 500 and 599 mse before action. An additional 3/57 conditions (5.3%, 3 unique studies) did not provide an average value either in text or in accompanying tables. Of these, one study reported that all W judgments were made 0–1000 msec before action (Bode et al. 2011), and another reported that 90.1% of judgments were made between 0 and 1000 msec before action, while 8.5% occurred between 1000 msec and 1500 msec before action (Soon et al. 2008). Eleven studies that provided average W values gave multiple values that tended to be clustered within the same grouping. Therefore, the trend observed here could be disproportionately affected by a few studies.

Of the studies that did measure W, many used recording techniques in conjunction with the measurement, including EEG (16/27 articles, 59.3%; 35/57 conditions, data not provided [DNP] for 1/35 conditions), fMRI (5/27, 18.5%; 5/57 conditions, DNP for 3/5 conditions) depth electrodes (1/27, 3.7%; 1/57 conditions, DNP for 0/1 condition), and EMG (1/27, 3.7%; 6/57 conditions, DNP for 0/6 conditions). Four

Table 1. Source of methods listed by each article in the sample.

Libet et al. 1983 only	**26/47**
Libet et al. 1983 and one other article	**9/47**
Haggard, Clark, and Kalogeras 2003	4/9
Banks and Isham 2009	2/9
Libet 1985	1/9
Haynes et al. 2007*	1/9
Lau et al. 2004	1/9
Other articles	**8/47**
Haggard, Clark, and Kalogeras 2002	3/8
Soon et al. 2008	2/8
Haggard and Eimer 1999	1/8
Haggard, Aschersleben, Gehrke, and Prinz 2002*	1/8
Sirigu et al 2004	1/8
No source provided	**4/47**

*Did not meet requirements for inclusion in the final sample.

of 27 (14.8%) did not use any specific recording technology in conjunction with W (10/57 conditions, DNP for 3/10 conditions). No studies involving TMS measured W.

In studies that recruited other groups, only meditators and patients with brain lesions, psychogenic tremor, or Gilles de la Tourette's (average value not provided) were asked to report W measurements. None of these values fell outside of those reported by healthy participants, although they were reported to vary significantly from control groups within their respective studies.

Average M Time (msec; Includes Libet et al. 1983)

Twenty-eight of 48 (58.3%) studies measured M. In total, average M values were reported for 74 conditions (see Figure 2). Of these, average values were not provided for eight conditions. Out of the conditions that measured M, 51/74 conditions (68.9%, 20 original studies) recorded M between 0 and 99 msec before the actual time of action. Fourteen of 74 conditions (18.9%, 7 original studies) found that the average M judgment occurred 1–99 msec after the time of action. One of 74 (1.3%, 1 original study) recorded an average M value more than 100 msec after action. No studies reported an M value occurring more than 100 msec in advance of action.

Various recording techniques were used to measure M values across the articles. The largest number of M measurements came from studies that did not use any recording techniques (17/28 articles; 54/74 conditions, DNP for 7/54 conditions). This was followed by EEG (7/28 articles; 14/74 conditions, DNP for 1/14 conditions), TMS (2/28 articles; 4/74 conditions, DNP for 0/4 conditions), and fMRI (2/28 articles; 2/74 conditions). No M measurements were recorded for the studies that used depth electrodes or EMG.

Roughly the same number of articles in this sample reported M and W measurements (see Figure 2). However, only 11 studies measured both M and W (out of a potential total of twenty-seven; 40.7%). Both M and W would need to be measured in order for the experiment to yield results comparable to Libet and colleagues' (1983) findings regarding voluntary action.

Neural Measurements (msec; Includes Libet et al. 1983)

RP can be measured by EEG. Out of the 19 studies that used EEG (19/48, 39.6%), 12/19 (63.2%) measured RP. A few of these studies (4/12; 33.3%) also measured other event-related potentials in addition to RP, such as event-related desynchronization[4] (ERD, 1/12; 8.3%), the lateralized readiness potential (LRP, 3/12; 25%) and slow cortical potentials[5] (SCPs, 1/12; 8.3%). Seven (36.8%) EEG trials did not measure the RP, 2/7 (28.6%) measured SCPS, 1/7 (14.3%) measured both LRP and movement-preceding negativity[6] (MPN), 1/7 (14.3%) measured ERD and event-related synchronization[7] (ERS), 1/7 (14.3%) measured action-effect negativity (N_{AE})[8] and P3,[9] and 1/7 (14.3%) measured surface Laplacians.[10] One of seven (14.3%) did not record neuronal activity (the goal of this study was to create a model by monitoring neural activity [Schneider et al. 2013]).

Very few papers in our sample provided the values for RP if they measured both LRP and RP.

4. Event-related desynchronization (ERD) refers to the localized phasic blocking or reduction in amplitude of beta and alpha bands that is related to an event. It is thought to be indicative of preparatory activity accomplished by neuronal structures in anticipation of sensory processing or the execution of a motor command (Pfurtscheller and Aranibar [1977], as cited in Pfurtscheller [1992]).
5. Slow cortical potentials (SCPs) are changes in the polarization measured by EEG that last from 300ms to several seconds in length. These polarizations can be either positive or negative (Birbaumer 1999).
6. Movement preceding negativity (MPN) is a general term that describes different types of negative polarization that are seen before action (Brunia 1988).
7. Event-related synchronization (ERS) is the opposite of ERD. It refers to the increase in localized alpha and beta activity in relation to activity. For more detailed information about ERS, refer to Pfurtscheller (1992).
8. Action-effect negativity (N_{AE}) refers to a signal that is elicited in response to unexpected and task-irrelevant action effects. The appearance to this signal is said to be similar in appearance to feedback-related negativity (N_{FB}), in which neuronal signals change following feedback related to the action that was performed (Waszak et al. 2012).
9. P3, or P300, is a positive component of the EEG signal that appears approximately 300 msec following an event (various sources, as cited in Duncan-Johnson and Donchin [1982]).
10. Surface Laplacians are a way of measuring neuronal current for high-resolution EEG. It is thought to be a superior way of measuring local cortical potential perpendicular to the scalp compared to the traditional way of measuring EEG. Surface Laplacians do not use a reference and are less affected by movement artifacts (e.g., blinking) (Nunez and Westdorp 1994).

Table 2. Articles included in the review characterized by grouping.

Group	1	2	3	4	5
Number of articles	15/48	8/48	14/48	6/48	5/48
Characteristic	No significant change to methods of Libet et al. 1983	Calculates the timing of decisions using a stream of letters rather than a clock.	Uses an auditory stimulus shortly after movement	Participants judge "active" and "passive" movements	Asks participants to alter their intention once they became aware of it
Total number of participants	240	159	294	114	76
Participant groups	Patient groups (5/15): various brain lesions, psychogenic tremor, epilepsy, Gilles de la Tourette syndrome	No patient groups.	Extensive meditation (1/14), Patient groups (4/14): deafferented subject, Parkinson's disease, schizophrenia, conversion disorder	No patient groups.	Extensive meditation (1/14), No patient groups
Used recording equipment	11/15	7/8	6/14; TMS 1/14	1/6; TMS used 1/6	5/5
Measurements:					
W only	6/15	6/8	4/14	0/6	3/5
M only	1/15	2/8	11/14	0/6	0/5
M and W	7/15	2/8	1/14	0/6	1/5
Neural	8/15 (RP)	4/8 (RP, LRP)	4/14 (RP, SCP, NAE/P3)	0/6	3/5 (RP, RP & SCP, ERD/ERS)
Recordings RP/LRP and W	3/15 (all RP & W)	3/8 (LRP & W – 2/3, RP & LRP & W – 1/3)	0/14	0/6	0/5

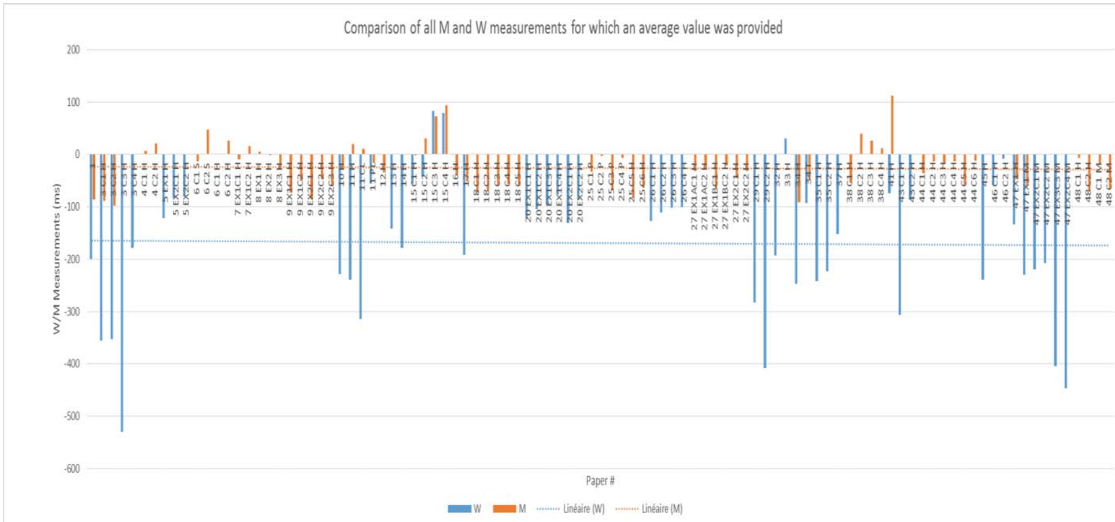

Figure 2. All M and W values for which an average value was presented in the original studies across all recording methods and ordered chronologically. Out of the 48 studies included in this sample, only 11/48 measured both M and W. (Color figure available online.)

RP, LRP, and W Comparisons (msec; Includes Libet et al. 1983)

Out of all of the studies that used EEG and, thus, could measure RP or LRP, only six (31.6%) compared W with RP, LRP, or both and provided average measurements (RP: 3/6; LRP: 2/6; both: 1/6). In total, these 6 articles provided 13 conditions that could be compared (12 with average values, 1 DNP) (see Figure 3).

None of the Group 1 articles that compared RP and W were done in an attempt to replicate previous findings. All of these articles reported that RP could be detected before W, although the difference between the reported measurements of RP and W was not consistent. None of these articles contained RP measurements that were within ±50 msec or ±100 msec of the time recorded by Libet et al. (1983).

Of the articles reporting values in Group 2 (Supplemental Table 2), Schlegel et al. (2013) conducted their work in an attempt to replicate the results of Haggard and Eimer (1999), but reported that they were unable to do so. Trevena and Miller (2002) found that RP always occurred before W, but they recorded several instances where LRP did not. The mean LRP average still occurred before W, but they concluded that LRP started after the participants' decision to move. In all, these three studies suggest that the relevance of LRP to W is not yet established.

The amplitude of RP was measured more frequently across the sample than the timing of the RP (amplitude

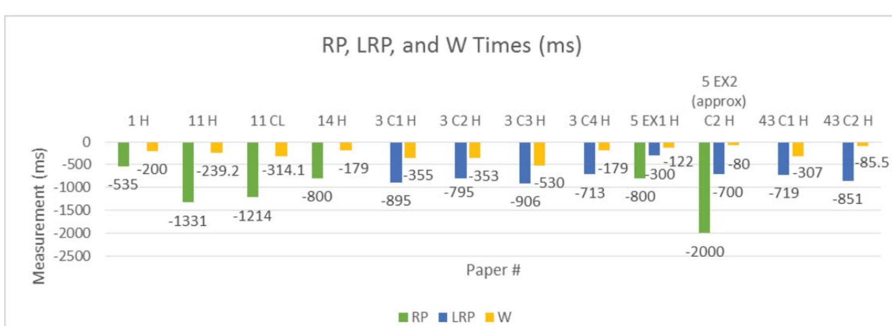

Figure 3. All comparisons of W and RP, LRP, or both mentioned within the sample. Out of all studies that used EEG, 6/19 papers compared W with either RP, LRP, or both and provided average measurements (RP: 3/6; LRP: 2/6; both: 1/6) for a total of 13 conditions (1 condition DNP). In number 5, only the RP value for statistical test (–800 msec) was included (the remaining measurement was RP values detected via visual inspection [–1300 msec]). The –80 msec value for 5 EX2 C2 H corresponds to the "hand" test (see Supplementary Figure), which is more directly comparable to number 3 and number 43 than 5 EX2 C1H. The RP value for number 1 represents the value of Type II RP, which was the type that Libet and colleagues used in their paper as indicative of W. (Color figure available online.)

measurements are not reported in this article). In addition to the 6/19 studies that compared the timing of W to RP and/or LRP, one article measured RP amplitude rather than timing in conjunction with W (Jo et al. 2014a; Jo et al. 2014b), two articles measured RP and W separately but did not compare them (Miller, Shepherdson, and Trevena 2011; Vinding, Jensen, and Overgaard 2014), one looked at ERS/ERD and W (Walsh et al. 2010), one said that the mean difference between RP onset and time of awareness was 267 ± 30 msec but did not provide W values (Keller and Heckhausen 1990), one compared W and surface Laplacians (Rigoni et al. 2013), one compared W and SCPs (Jo et al. 2013), and one looked at N_{AE}/P3 and W (Rigoni, Brass, and Sartori 2010).

Neural Correlates of Studies (Includes Libet et al. 1983)

Several articles mentioned regions of the brain that were possibly related to their study findings (14/48 (29.2%)). Eight of 48 (16.7%) reported differences in activation between electrodes without referencing underlying neural structures, and an additional 12/48 studies (25%) mentioned that the studies' results indicated the involvement of some nonspecified neuronal processes. Several studies did not measure or mention whether their results correlated with different brain areas (14/48; 29.2%).

The studies in our sample associated activation with large swaths of the cortex and did not identify a clear neural origin of free will/voluntary action. The pre-supplementary motor area (pre-SMA) and the supplementary motor area (SMA) were the two areas that were the most frequently identified ($n = 4$ and $n = 7$, respectively, although four of these studies mentioned both areas). Neural activity was recorded broadly across the frontal and parietal lobes (see Figure 4).

Interestingly, 12/14 articles that referenced the involvement of a specific brain region in the experience of awareness of action did not use any neuroimaging technique. While most of these were just general statements, two papers specifically identified the dopamine system as having a role in one's sense of agency (Haggard et al. 2003; Moore et al. 2010). In the first paper, the authors speculated that the tendency of schizophrenic participants to overattribute consequences to their own agency could be linked to the excessive dopamine transmission that is thought to be present in individuals with this disorder (Haggard et al. 2003). In the second, authors compared the action-binding effect across three groups (those with Parkinson's disease on and off dopaminergic medication and healthy controls). They reported increased action-effect binding in PD patients on medication when compared to both healthy controls and when the PD patients were off medication. From this, they stated that their data "clarifies the neural basis of [sense of agency], by showing a clear link to dopamine" and suggested that the "boosting of action-effect binding in PD patients *on* medication may be due to an overdosing of the ventral striatal dopamine system" (Moore et al. 2010, 1131, emphasis in original). However, these authors did not measure the action of any dopaminergic systems during their experiment.

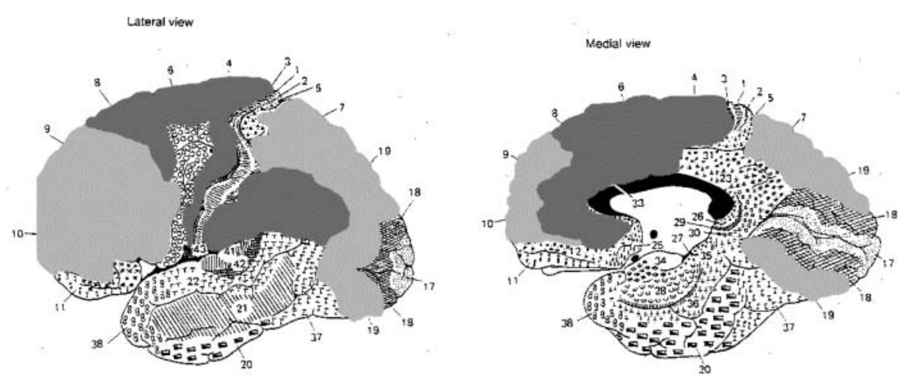

Figure 4. Articles in our sample identified several neural areas that they associated with free will and/or related concepts. These findings were spread across large swaths of the cortex and were not localized to particular areas. The dark area indicates Brodmann areas that were specifically indicated in individual studies. Lighter shaded areas indicate areas mentioned in studies that have been roughly mapped onto a Brodmann map. Areas mentioned in our sample included pre-SMA, SMA, medial premotor system, lateral premotor system, right dorso-prefrontal cortex, medial prefrontal cortex left intraparietal sulcus, anterior cingulate cortex, primary motor cortex, bilateral motor cortices, right visual area V5 (V5/MT), Brodmann Area (BA) 10, medial frontopolar cortex, left frontopolar cortex, parietal cortex (precuneus to posterior cingulate cortex), rostral cingulate zone, default mode network, angular gyrus, right frontal eye field, left superior parietal cortex, right intraparietal cortex, left supramarginal gyrus, right ventral thalamus, cingulate motor area, BA 9, bilateral anterior ventral insula, right superior temporal sulcus, left inferior parietal lobule (extending to left superior temporal gyrus and left dorsal premotor cortex), paracingular gyrus, lower precuneus, right superior frontal gyrus, right inferior frontal gyrus (pars opercularis/triangularis, BA 44/45), BA 19, BA 13, and BA 7.

DISCUSSION

Replications of the Paradigm and Its Connection to Intention

Despite the fact that almost 50 articles qualified for inclusion in this review, very few completely replicated Libet and colleagues' (1983) methods or were able to report the same findings. In cases where experiments were explicitly conducted to replicate other experiments (Libet et al. 1983, and others), most were unable to produce similar results (see Bode et al. 2011; Lafargue and Duffau 2008; Lages and Jaworska 2012; Lau, Rogers, and Passingham 2006; Schlegel et al. 2013; Strother and Obhi 2009). Furthermore, some authors chose to critique Libet and colleagues' (1983) conclusions, methods, or interpretations by deliberately altering the paradigm to demonstrate how these alterations affected the results (see Keller and Heckhausen 1990; Lau, Rogers, and Passingham 2006; Miller, Shepherdson, and Trevena 2011; Rigoni, Brass, and Sartori 2010; Trevena and Miller 2002; Trevena and Miller 2010). The actual methods used by those who credit Libet and colleagues (1983) as the source for their methods vary considerably. From these variations, we were able to describe five different subtypes of the Libet and colleagues paradigm that have emerged over the years (see Table 2 and Supplementary Table 2). These subtypes differed by the actions that participants were instructed to perform, but still ascribed their methods to Libet et al. in some way. The variability between these subtypes poses problems for the view that Libet and colleagues' (1983) methodology has been replicated successfully and is thus a viable method to study awareness of action (Haggard 2005). It could be argued that the fairly stable trend lines presented in Figure 2 and the variability in measurements for both the M and W measurements across the groups (see Figures 3 and 4) suggests that the effect is robust across the Libet paradigm subtypes. However, the fact that some groups and articles yielded a disproportionate number of measurements makes it difficult to make conclusions based on these data. For example, only 6/48 articles actually compared LRP/RP and W. Furthermore, Group 3 contained 39.3% of articles that measured M, but the measurements gained from this subtype accounted for 51.4% of all M measurements.

Some later articles that deviated from Libet and colleagues' technique have become paradigmatic in their own right, with other articles citing them heavily instead of Libet et al. (1983). The most emblematic example of this is Haggard, Clark, and Kalogeras (2002). This study was the first to alter Libet and colleagues' (1983) method by adding an auditory tone. Articles that cited Haggard Clark, and Kalogeras (2002) as the primary source for their methods did not always reference Libet et al. (1983) as the original source, even though Haggard, Clark, and Kalogeras (2002) had credited this paper themselves. Haggard, Clark, and Kalogeras (2002) is also notable for introducing the concept of intentional binding, which refers to "the subjective compression of the temporal interval between a voluntary action and its external sensory consequence" (Haggard, Clark, and Kalogeras 2002; Moore and Obhi 2012). Although intentional binding is often assumed to have a link with one's sense of agency and, thus, free will, the link between these two concepts has not been fully elucidated (Moore and Obhi 2012).

Measurements and Their Relationship to Voluntary Action

The results of Libet-like experiments are often used to support the idea that intentional action originates from certain brain regions or as an example of neuroscientific data that can be used in support of various philosophical positions about free will. However, many studies in our sample did not record neural activity. Inconsistencies in electrode placement, positioning of other recording apparatuses, the ways measurements were analyzed, and the fact that multiple conditions were reported by many papers made it difficult to pinpoint the most common source of action potentials. Studies referred to various areas across the frontal and parietal lobes as being relevant to voluntary action (see Figure 4). The SMA and pre-SMA were referred to more frequently than other areas, although the specificity of activity locations varied between trials. It is possible that this variation in activation occurred because some experiment alterations required different processes. Efforts that have been made to illuminate the pathways involved in volition often suggest that many different brain regions are involved (Brass and Haggard 2008; Brass et al. 2013; Haggard 2008; 2009; Hallett 2007; Libet, Freeman, and Sutherland 1999; Pierre 2014; Rappaport 2011; Wolpe and Rowe 2014).

Many more measurements were recorded for M ($N = 74$) than for W ($N = 57$), even though roughly the same number of articles measured these two types of judgments (28 and 27 articles, respectively). The legacy of the Libet and colleagues (1983) study for free will and voluntary action rests mostly on the association with W and the RP measurements. While there seems to be a trend of W and M measurements occurring between 150 and 200 msec before movement (W) or between 0 and 50 msec before movement (M), it would be inappropriate to say that this is the average measurement due to (1) statistical errors when calculating an average using averages, and (2) the fact that some articles provided multiple average values for M or W that could skew the results. Few articles measured RP or LRP in conjunction with W, even though it is often assumed that RP/LRP reflects W or intentional action more broadly (e.g., see Libet, Wright, and Gleason 1982; Radder and Meynen 2013; Schlegel et al. 2013). Articles that actually did compare RP or LRP to W often found conflicting results (Haggard and Eimer 1999; Schlegel et al. 2013; Trevena and Miller 2002).

Studies that used fMRI or looked at other recordings than RP or LRP often observed significant changes in activation several seconds before awareness. However, technical limits of the device were used in these cases to posit that the true results occurred in advance of what was able to be measured (i.e., several seconds were added to recorded values to account for the sluggishness of the BOLD response and fMRI's low temporal resolution). Additionally, several studies focused on developing models to predict or identify the location of neural activity even when its relation to voluntary action had not been established.

While this work may indicate the typical range within which M or W will fall, it does not solidify the relationship between the type of neural activity observed and M/W. The average values reported by most studies occur in advance of awareness, but these findings do not establish the relation between this activity and awareness of action. Additionally, much of this work does not address a common criticism (Banks and Pockett 2007; Klemm 2010; Roskies 2010) that simple finger flexions and complex, deliberative action are very different. Clearly, much more work needs to be made to establish this connection for Libet-like experiments to be used to support any philosophical position about free will.

The Libet Paradigm and Its Societal Implications

The variation present in our review poses problems for (a) comparing results between studies, (b) evaluating the relevance of this type of methodology to answering questions about voluntary action, and (c) extrapolating its significance to society as a whole. Furthermore, even if we assume that each experiment was an exact replication of the original paper, some of the claims made in individual papers would not be supported by the methods employed. For example, a few papers claim to have clarified the "neural basis of SoA [sense of agency]" by linking the awareness of voluntary action and dopamine transmission through the involvement of populations with Parkinson's disease or schizophrenia (Haggard et al. 2003; Moore et al. 2010, 1131). While this is an interesting hypothesis, neither of these papers directly measured dopamine transmission in the brain and they instead either used proxy methods (e.g., whether or not individuals were taking medications like L-DOPA [Moore et al. 2010]) or inferred the connection from other articles (Haggard et al. 2003). Other studies claim that differences between individuals with neurological conditions and healthy controls point to sense of agency as responsible for a loss of control: for example, that "an excessive sense of agency may contribute to impulse control disorders" (Moore et al. 2010) and that "the defining characteristic in motor [conversion disorder] is not the type of movement but, rather, a reduced or altered sense of agency for movement" (Kranick et al. 2013). However, as has been argued elsewhere, a "structural or functional abnormality in a circumscribed area of the brain associated with impulse control does not imply the loss of the ability to control impulses" (Glannon 2011). Additionally, observations from these populations did not fall outside the measurements obtained from healthy populations in other studies (see Supplementary Table 2), indicating that the significant differences uncovered in the study may be the result of small sample sizes.

Probably the most discussed conclusion generated by the Libet paradigm is whether this method adds support to the idea that neuroscientific studies prove that free will does not exist (Wegner 2004). A thorough analysis of the arguments for and against its existence and the relevance of neuroscientific findings to this debate is outside the scope of this article. However, it is important to note (as others have before) that, traditionally, actions designated as voluntary are complex, and not simple finger flexions. Additionally, research suggests that the layperson's understanding of freedom of action is neither dualistic nor indeterministic (Monroe and Malle 2010), and that the attribution of responsibility does not change even if "my brain made me do it" (Nahmias, Shepard, and Reuter 2014). Therefore, statements that any individual study could have "important implications for the notion of conscious intention in moral and legal situations" (e.g., Haggard et al. 2004) may be premature.

LIMITATIONS

In our analysis, we restricted comparison between studies to those that were most similar to Libet and colleagues' (1983) original methodology, as well as to those that explicitly cited Libet and colleagues (1983), Libet (1985), and Soon et al. (2008). It is possible that the results of the included studies differ due to variation in individual experiments, rather than Libet and colleagues' (1983) methodology itself. However, these experiments are often compared indiscriminately in the literature. Additionally, we acknowledge the existence of a publication bias, which favors experiments that are considered novel or as having great contributions to the field (Rothstein, Sutton, and Borenstein 2005). For example, it is possible that other experiments that either replicated all aspects of Libet's study or did not find the same pattern of results were not published. We also are aware that not all articles that report intentional binding were captured in this work. Finally, while we tried to base the inclusion criteria for studies on the aspects of the trial design that were included in most papers, ultimately this paradigm defies a clear boundary.

CONCLUSION

This study adds to existing research findings by typifying the different ways that the Libet et al. paradigm has changed over time, and by comparing the findings produced across the different subtypes. The findings of Libet and colleagues' (1983) experiment, and those who follow this methodology, have been very influential. While almost all papers in our review reported a general pattern of average neural activity occurring before participants' awareness of their intention to act, the relationship of this activity to their intention still needs to be established. We were able to identify five main subtypes of the Libet and colleagues experiment that have emerged since 1983. In doing so, we highlighted the differences between (a) the measurements recorded in each type and (b) how these measurements differ between the subtypes. While the overall trends for W and M seem consistent across all of the articles when ordered chronologically, most of the "M" measurements come from Group 3. No "W" measurements came from Group 4. Additionally, the overall number of W and M measurements across all groups are higher than expected because many articles present more than one measurement. Therefore, while the Libet paradigm may be useful for examining the time needed to respond following an external stimulus or how external stimuli affects temporal judgments, it may be inappropriate at this time to extrapolate results gained from this methodology to discussions about freedom of action or moral responsibility.

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