Acta Psychologica 191 (2018) 228–233

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

One hundred fifty years after Donders: Insights from unpublished data, a replication, and modeling of his reaction times☆

Ardi Roelofs*

Radboud University, Nijmegen, the Netherlands

ARTICLE INFO

Keywords:
Choice
Executive control
Individual differences
Modeling
Reaction time
Speech repetition

ABSTRACT

Mental processes take a measurable amount of time, which was discovered by Donders one hundred fifty years ago. He reports process durations in his classic study with the a-, b-, and c-methods (i.e., simple, choice, go/no-go) using a speech repetition task. His reaction time pattern was a < c < b. He reasoned that the c – a difference gives the discrimination duration, and the b – c difference the choice duration. A few years later, Wundt criticized the c-method by arguing that it does involve a choice (i.e., whether or not to respond, which is an act of executive control), whereas Donders maintained that it may not involve full discrimination. The substance of this historical controversy relates closely to modern issues in the study of reaction times. Here, I show that an analysis of unpublished data from a handwritten laboratory notebook of Donders reveals no b – c difference for his students, supporting Wundt's concern. Moreover, a replication of Donders' study using his original stimulus lists yielded only a small b – c difference for myself, supporting Wundt. A computer simulation using a modern model of speech repetition indicates that the difference between Donders and his students may plausibly result from choice in the c-method. To conclude, unpublished data, a replication, and modern modeling resolve a 150-year-old issue, stressing the importance of examining individual differences and executive control in performance.

1. Introduction

Mental processing times were first measured 150 years ago. On Monday, August 21, 1865, Donders conducted his seminal study with the a-, b-, and c-methods (i.e., simple, choice, go/no-go) using a speech repetition task, reported in his landmark article a few years later (Donders, 1868). An English translation of this article appeared in *Acta Psychologica* in 1969. Under the a-method, person A spoke a known syllable and person B had to repeat it as quickly as possible, under the b-method one of five syllables was spoken and had to be repeated, and under the c-method one of five syllables was spoken but only a specific one had to be repeated. Donders reasoned that the a-method requires no perceptual discrimination and no motor choice, because person B hears only one syllable and makes a predetermined response. The b-method requires discrimination and choice, because the person has to determine which of the five syllables is heard and has to choose the corresponding motor response. The c-method requires discrimination but no choice, because the person has to determine which of the five syllables is heard but makes a predetermined response. Therefore, subtracting the reaction time (RT) for the a- from the c-method should give the discrimination duration, and subtracting the RT for the c- from the b-method gives the choice duration. The estimates of the discrimination and choice durations that Donders obtained were 0.036 and 0.047 s, respectively, demonstrating that mental processes take time.

With his seminal observations, Donders (1868) laid the foundation of a research paradigm that is still extremely productive in psychology, namely the chronometric analysis of human performance (e.g., Gazzaniga, Heatherton, & Halpern, 2015; Luce, 1986; Posner, 1978, 2005; Sanders, 1998; Sternberg, 1969), see Draaisma (2018) and Levelt (2013) for historical perspectives. As Luce (1986) stated, “Response time is psychology's ubiquitous dependent variable. No matter what task a subject is asked to do in an experiment, its completion always takes time” (p. 1). Moreover, Donders' subtraction method provided the

☆ The research reported in this article commemorates the 200th birthday of F. C. Donders (1818–1889), the 150th publication anniversary of his classic article (Donders, 1868), and the 50th publication anniversary of its English translation in *Acta Psychologica* (Donders, 1969). I thank Pim Levelt, James McQueen, and Sieb Nooteboom for helpful discussion, and Sterre Roelofs for helping with the experiment.

* Corresponding author at: Radboud University, Donders Institute for Brain, Cognition and Behaviour, Centre for Cognition, Spinoza Building B.02.34, Montessorilaan 3, 6525 HR Nijmegen, the Netherlands.

E-mail address: A.Roelofs@donders.ru.nl.

https://doi.org/10.1016/j.actpsy.2018.10.002
Received 10 July 2018; Received in revised form 10 October 2018; Accepted 12 October 2018

basic design logic of studies in the early days of modern neuroimaging (Posner & Raichle, 1994; Raichle, 1998). Interestingly, imaging techniques such as positron emission tomography and functional magnetic resonance imaging exploit a phenomenon that Donders (1849) had observed with his own eyes in examining blood flow in a rabbit. He perceived that "the blood undergoes a change as a consequence of the nourishment of the brain", and that one "discovers in comparing the incoming and outflowing blood that oxygen has been consumed" (Donders, 1969, p. 412).

Although the demonstration of mental processing time by Donders (1868) was readily accepted, the accuracy and validity of the estimates obtained with his methods were questioned (see Meyer, Osman, Irwin, & Yantis, 1988, for a brief historical review). In particular, Wundt (1874) criticized the c-method by arguing that it does involve a choice, namely whether or not to respond. Cattell (1886) expressed the same concern. This concern implies that the difference in RT between the b- and the c-methods underestimates the motor choice duration. Donders himself expressed a different concern, namely that the c-method may not involve full discrimination. In reviewing the literature on Donders' subtraction method, Luce (1986) noticed that the issue raised by Wundt has not been resolved (see also Ulrich, Mattes, & Miller, 1999). The substance of the historical controversy relates closely to modern issues in the study of RTs, including the relationship between two-choice and go/no-go procedures (i.e., b- and c-methods) with manual responding (Gomez, Ratcliff, & Perea, 2007; Vidal, Burle, Grapperon, & Hasbroucq, 2011) and individual differences in the go/no-go procedure (Bender, Filmer, Garner, Naughtin, & Dux, 2016; Ratcliff, Huang-Pollock, & McKoon, 2018). A go/no-go decision is an act of executive control (e.g., Diamond, 2013), which contributes to speech production times (e.g., Shao, Roelofs, & Meyer, 2012; Sikora, Roelofs, Hermans, & Knoors, 2016).

The aim of the work reported in the present article was to commemorate the work of Donders by addressing this unresolved controversy concerning the c-method for speech repetition. Section 2 examines the classic RT study of Donders (1868) in more detail. Section 3 reports an analysis of unpublished RT data from Donders' students that I discovered in a handwritten laboratory notebook of Donders (1865). Section 4 presents the results of a replication of Donders' classic study using all his original stimulus lists. Section 5 reports the results of a computer simulation of the performance of Donders and his students using a modern computational model of speech repetition.

2. Donders' classic study

Donders was inspired to do his work on mental processing speed by earlier research of his friend Helmholtz on the speed of nerve conduction (Helmholtz, 1850). In his studies, Helmholtz electrically stimulated a motor nerve of a frog at two distances from the muscle, and measured the muscle contraction time as a function of the stimulation distance. This lead to an estimate for the speed of nerve conduction of about 30 m per second. Donders performed similar experiments in humans, in which he stimulated the skin at different distances from the brain (e.g., foot vs. groin) and asked for a manual response to the stimulation. The laboratory notebook of Donders (1865) reveals that his daughter Marie and his friend the ophthalmologist William Bowman were among the subjects.

2.1. Measuring the speed of mental processes

The experiments to measure the speed of nerve conduction used what Donders (1868) called the a-method: a single stimulus and a single response. He reasoned that by using other methods, the speed of mental processes could be determined. Donders had used the a- and b-methods (i.e., simple and choice) in June 1865 with manual and spoken responses (see the dissertation of De Jaager, 1865). His laboratory notebook (Donders, 1865) suggests that the full hierarchical design with the a-, b-, and c-methods was employed for the first time in August 1865 using a speech repetition task. Different from what is sometimes suggested (e.g., Vidal et al., 2011, p. 1242), Donders did not use the full hierarchical design with manual responding. To measure speech repetition RTs, Donders used the "phonautograph" and "noematachograph", which are illustrated in Fig. 1.

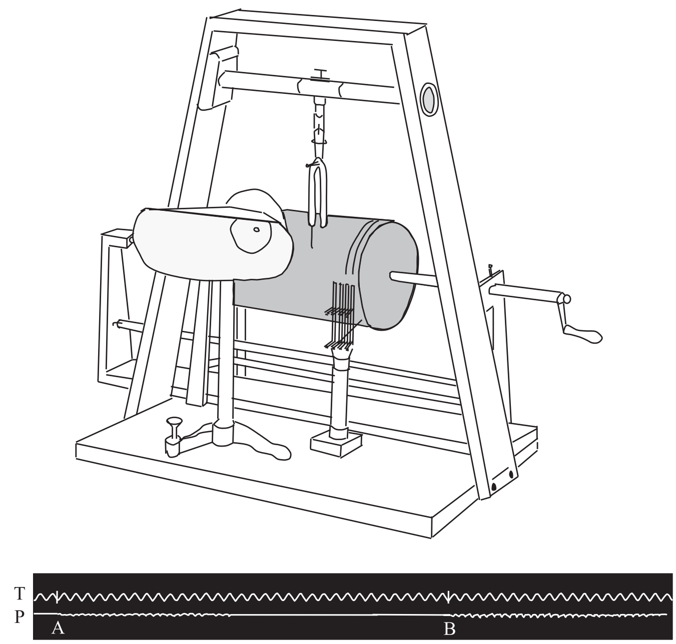

Fig. 1. Stylized versions of the phonautograph and noematachograph, and the noematachogram from Donders (1868) showing the speech waves of two persons (P), the sound wave of a tuning fork (T), and vertical marks indicating the speech onsets (A and B) of the persons.

Two persons A and B were seated before the mouth of the phonautograph. While the cylinder was rotated by the experimenter, person A spoke a syllable and person B repeated it as quickly as possible while trying to make no mistakes. Their speech waves were marked on sooted paper that covered the cylinder. The RT is the time interval between syllable onsets (A and B), which Donders deduced by counting the corresponding number of oscillations of a tuning fork (T) recorded simultaneously, irrespective of their length (i.e., a constant speed of rotation of the cylinder is not required).

Donders also used the noematachograph to present visual, non-vocal auditory, or tactile stimuli (as he had done in experiments with his daughter and others) and to record the corresponding manual RTs. To this end, there were two disks on the right side of the cylinder, which were partly covered with brass and partly with ebonite. Pairs of electrodes contacted the discs, and induced and stopped an electric current that controlled the presentation of stimuli when the cylinder was rotated.

On each a-method trial with the speech repetition task, person B repeated a known syllable spoken by person A (i.e., "ki"). On each b-method trial, person B repeated an unknown syllable spoken by person A (i.e., "ka", "ke", "ki", "ko", or "ku"). On each c-method trial, person B repeated only a specific syllable spoken by person A (i.e., "ki"). Donders used lists consisting of 22 stimuli ordered as three a-trials, three b-trials, ten c-trials (with four or five go-trials), three b-trials, and three a-trials. These 22 trials were recorded one after the other on one sheet of sooted paper.

In his classic article, Donders (1868) reports the RT data for his student Hamer as person A and himself as person B (henceforth Hamer–Donders). His mean RTs across three stimulus lists (i.e., lists 15, 16a, and 16b, see Donders, 1865) for the a-, b-, and c-methods were 201 ms, 284 ms, and 237 ms, respectively. His discrimination duration (c – a) was estimated to be 36 ms, and the estimate of his choice duration (b – c) was 47 ms.

2.2. *What is in the noematachogram?*

The classic article of Donders (1868) has one figure of a noematachogram, illustrated in Fig. 1. Donders does not say much about the noematachogram. Although it has been suggested that the noematachogram depicts a /ki/–/ki/ trial (e.g., Schmidgen, 2005), evidence for this assumption is lacking. A decade ago, Feaster and Cornell made a high-resolution scan of the noematachogram and used modern computer software to make an audio reconstruction of the sound waves (see http://firstsounds.org). They discovered that the tuning fork of Donders was likely 130.5 Hz rather than 261 Hz, as suggested by Donders' specification of "261 vibrations" (which apparently refers to half-cycles). Which syllables are encoded by the noematachogram and who are the speakers?

2.2.1. *Method*

To examine the noematachogram, I employed Donders' own discovery that vowels are characterized by their overtones, independent of the fundamental frequency (Donders, 1864). "Whatever the pitch of the voice with which it is produced, for each vowel the tuning of the oral cavity is absolute, …, and in this connection any vowel has its absolute, virtually invariant harmonics" (Donders, 1969, p. 423). In modern phonetics, the fundamental frequency is referred to as F_0, and the first two overtones as formants F_1 and F_2. The upper panel of Fig. 2 shows the oscillogram of the audio reconstruction by Feaster and Cornell, which I obtained using the software package Praat (Boersma & Weenink, 2016). The lower panel shows the oscillogram after filtering by my colleague James McQueen. To remove the very low frequency oscillation, a high-band-pass filter was applied to cut all energy below 20 Hz. Next, a low-band-pass filter was applied to cut all energy above 3500 Hz. I performed a formant analysis using Praat.

2.2.2. *Results*

The formant analysis showed that the F_0, F_1, and F_2 of person A were 111 Hz, 235 Hz, and 663 Hz, and those of person B were 221 Hz, 256 Hz, and 699 Hz. The fundamental frequency suggests that the first person is a man (as expected) and the second person a man responding quickly (as expected) or a woman. Moreover, the two formants indicate that the vowel is likely an /u/ (F_1 = 339 Hz, F_2 = 810 Hz) rather than an /i/ (F_1 = 294 Hz, F_2 = 2208 Hz), see Pols, Tromp, and Plomp (1973). Other vowels in Dutch all have a higher F_2 than observed here. The oscillogram does not provide any evidence that the vowel is preceded by a consonant (i.e., /k/).

The laboratory notebook of Donders (1865) reveals that experiments with /u/ (without preceding consonant) have been done on Saturday, December 23, 1865, with Bowman as person A and Donders as person B. Trial 17 of list 46 involved /u/–/u/, whereby the response took 66.9 tuning-fork vibrations to give. This corresponds closely to the RT that can be derived from the noematachogram (counting half-cycles). Thus, the best guess is that the responding person in the noematachogram is Donders himself.

3. Analyzing Donders' unpublished work

In discussing the results of the speech repetition study with the a-, b-, and c-methods, Donders (1868) notices that the c-method sometimes causes difficulty for persons:

> "It has appeared to me that to many people the c-method offers certain difficulties. They give the response, when they ought to have remained silent. And if this happens only once, the whole series must be rejected: for, how can we be certain that when they had to make the response and did make it, they had properly waited until they were sure to have discriminated? … For that reason I attach much value to the results … obtained with myself as a subject … in which the experiments turned out to be faultless" (Donders, 1969, p. 424)

If subjects respond before full discrimination on go-trials under the c-method, then the RT is shorter than it should be. Consequently, the b – c difference will overestimate the choice duration, and the c – a difference will underestimate the discrimination duration. The laboratory notebook of Donders (1865) revealed that on August 21, 1865, he also measured the RTs of his students Hamer and Stark, which may be used to evaluate his concern.

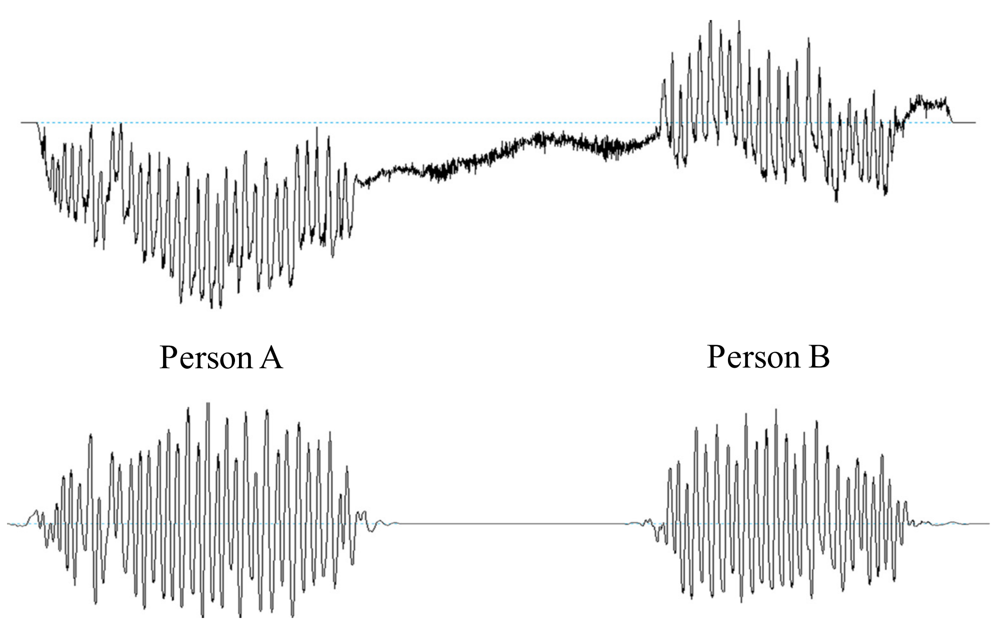

Fig. 2. Upper panel: An oscillogram of the audio reconstruction by Feaster and Cornell of the speech encoded by the original noematachogram of Donders (1868). Lower panel: The oscillogram after filtering.

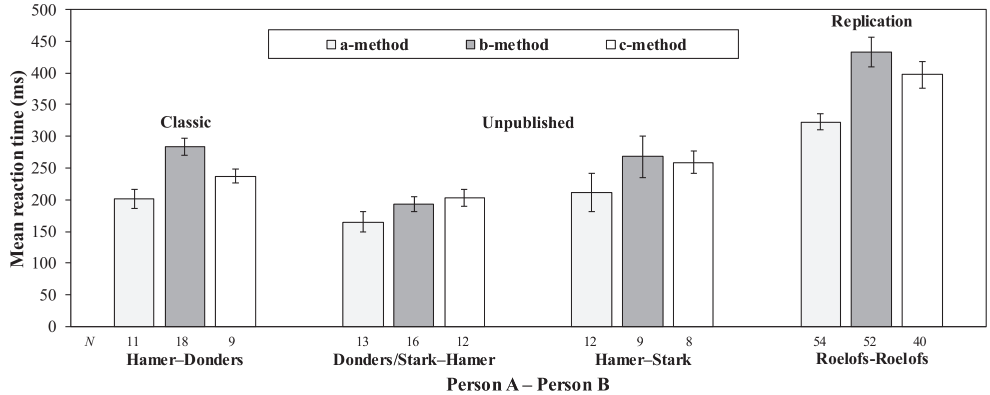

Fig. 3. The classic data reported by Donders (1868) and the unpublished data from his laboratory notebook (Donders, 1865). *N* = number of trials. The error bars indicate the 95% confidence intervals.

3.1. Method

I computed the RTs based on the records of tuning-fork vibrations and experimental notes available from the laboratory notebook of Donders (1865). The records and notes concerned lists 17a and 17b for Donders–Hamer, lists 18a and 18b for Stark–Hamer, and lists 19a and 19b for Hamer–Stark. The experimental notes suggest that Hamer and Stark sometimes did not respond when they ought to have responded on c-method trials. Thus, they omitted responses on go-trials rather than inadvertently responded on no-go trials.

3.2. Results

The leftmost graph in Fig. 3 depicts the earlier discussed, published mean RT data for Hamer–Donders (lists 15, 16a, and 16b), and the two graphs in the middle of Fig. 3 depict the unpublished mean RT data for Hamer and Stark. The performance of Hamer concerns the mean RTs across Donders–Hamer and Stark–Hamer (who had similar RT patterns) to increase the number of trials.

The figure shows that whereas Hamer and Stark replicated the RT pattern of Donders for the a- and c-methods (i.e., a < c), the RTs for the b- and c-methods do not really differ (i.e., b = c), taking the 95% confidence intervals into account (Cumming, 2014). This suggests that there are individual differences in performance under the c-method. If subjects do not await full discrimination before responding on go-trials, the RT will be shorter than it should be, and the b – c difference will increase. However, different from this, the RTs for the c- and b-methods of Donders' students did not really differ. This cannot be explained by assuming a reduced discrimination duration under the c-method, but instead suggests difficulty in choosing to respond. This would increase the RT for the c-method and reduce the b – c difference, as observed for Donders' students. Thus, the students of Donders had difficulty making the go/no-go decision, in line with the suggestion of Wundt, rather than awaiting full discrimination, as suggested by Donders.

4. Replication of Donders' classic study

An essential aspect of science is the ability to repeat studies and to obtain similar results (e.g., Cumming, 2014). I am not aware of any previous attempt to directly replicate the original /ki/–/ki/ study of Donders (1868). Given the difference in performance between Donders and his students, such a replication is warranted.

4.1. Method

To examine whether the RT pattern of Donders himself (a < c < b) is replicable, I conducted Donders' classic study using his original stimulus lists, available from his laboratory notebook (Donders, 1865). I used all nine lists that were used on August 21, 1865. In the replication, these lists were presented in random order. There were 54 a-method trials, 54 b-method trials, and 90 c-method trials, of which 40 required a reaction. Thus, the total number of trials was 198. Praat was used to record the speech and to graphically determine the RTs based on the speech waveforms. Thus, I used a graphical method for measuring RTs, as Donders did. My daughter Sterre was person A and I was person B. Fig. 4 illustrates one of the trials (i.e., /ki/–/ki/). The raw RT data are available from the archive of the Open Science Framework (osf.io/5ryq4).

4.2. Results

I performed correctly on 196 trials and failed to respond on two trials, which were b-method trials. The rightmost graph in Fig. 3 depicts the mean RTs. The graph shows that my own RT pattern corresponds to the pattern of Donders rather than his students. However, there are also some differences. First, my RTs are longer than those of Donders and his students (i.e., some 130 ms). Second, whereas the discrimination and choice durations for Donders himself were about equal, the replication reveals a smaller choice than discrimination duration for myself. Under Wundt's account, this would suggest that the go/no-go decision took more time for me than for Donders. Again, individual differences in c-method performance are observed for the speech repetition task, underlining the importance of examining individual differences in task performance (e.g., Jongman, Roelofs, & Meyer, 2015; Shao et al., 2012; Sikora et al., 2016).

To conclude, the classic RT pattern is replicable. However, my reduced choice duration suggests that I had some difficulty in making the

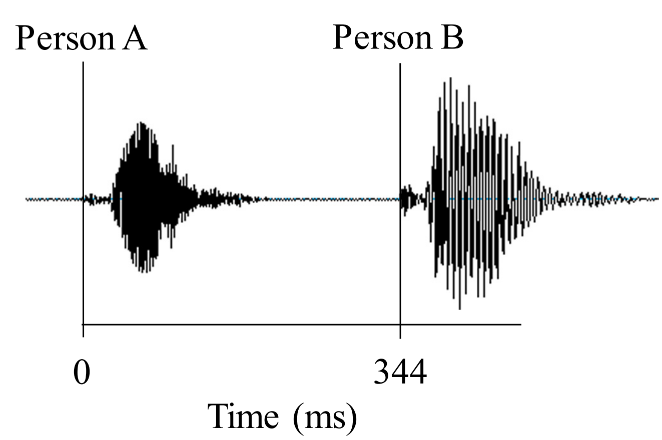

Fig. 4. Illustration of an experimental trial with person A saying /ki/ and person B repeating it. The vertical lines indicate their speech onsets.

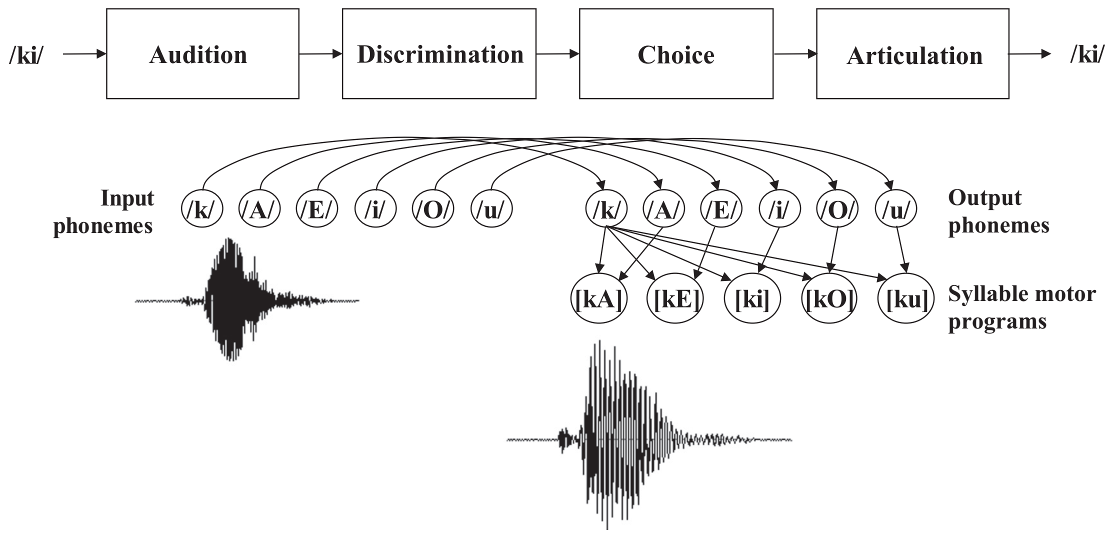

Fig. 5. The structure of the WEAVER++ model used in the simulation of Donders' classic study.

go/no-go decision, in line with the theoretical view of Wundt (1874).

5. Modeling of Donders' classic study

Models of speech repetition have already existed for over 150 years (Levelt, 2013). Repetition of speech was at the heart of the classic anatomical-functional model of spoken word recognition and production advanced by Wernicke (1874). Repetition performance has figured prominently in aphasiology during the past century, because it differentiates between types of aphasia (e.g., Geschwind, 1970). Computational models of speech repetition in aphasia address repetition accuracy but not RT (e.g., Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). To obtain a proof of concept for Wundt's account of performance under the c-method, and to account for individual differences, I simulated Donders' classic study using a modern computational model that addresses RT data, namely WEAVER++ (Levelt, Roelofs, & Meyer, 1999; Roelofs, 1997, 2014).

5.1. Method

The structure of the model used in the simulation is illustrated in Fig. 5. Given that Donders asked for the repetition of syllables rather than words, I used only the part of the WEAVER++ model that includes input and output phonemes, and syllable motor programs. To simulate Donders' classic study, the input and output phonemes /k/, /A/, /E/, /i/, /O/, and /u/, and syllable motor programs for [kA], [kE], [ki], [kO], and [ku] were used (the sound symbols are from the Computer Phonetic Alphabet), making up the model's declarative knowledge about the syllables in the experiment. Hearing a syllable was simulated by activating the corresponding input phonemes (e.g., /k/ and /i/) over time, which activated the corresponding output phonemes (i.e., /k/ and /i/) and syllable motor programs (e.g., /k/ activates all syllable motor programs with this phoneme). After discriminating the heard input phonemes, the corresponding output phonemes were syllabified and the matching syllable motor program was chosen. The model accomplishes this by condition-action rules, which make up procedural knowledge about the speech repetition task and how to operate under the a-, b-, and c-methods (i.e., executive knowledge).

On a-method trials, the motor program (i.e., [ki]) was chosen before trial onset, and its articulation was initiated as soon as the /k/ was heard. On b-method trials, detecting the /k/ was not sufficient but also vowel discrimination was needed, after which the corresponding output phonemes were syllabified and the matching syllable motor program was chosen. On c-method trials, vowel discrimination (i.e., /i/) was also needed and then articulation of the already chosen motor program (i.e., [ki]) was initiated. The parameter values in the present simulation were the same as in earlier simulations (Roelofs, 1997, 2014). An absolute activation threshold for input consonant detection on a-method trials, a differential threshold for input vowel discrimination on b- and c-method trials, and a differential threshold for the choice of the syllable motor program on b-method trials were all set to 1.0. Performance on c-method trials was simulated with a go/no-go choice after input vowel discrimination, which is an act of executive control whose duration was set to < 25 ms (negligible cost) or 75 ms (substantial cost) to fit the individual differences in the empirical data. The WEAVER++ simulation was computationally implemented using the C programming language and the programming environment of Microsoft Visual C++ 2017. The source code of the simulation program is available from the archive of the Open Science Framework (osf.io/5ryq4).

5.2. Results

Fig. 6 shows the simulation results, which are mathematically derived expected values without sampling error. Assuming a negligible

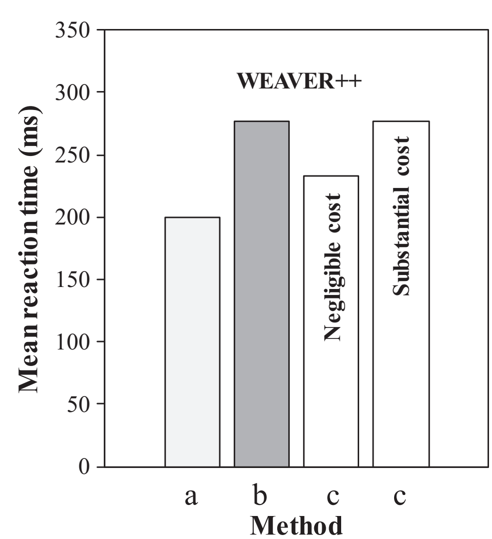

Fig. 6. Results of the WEAVER++ simulation of the classic study of Donders (1868), assuming a go/no-go choice of negligible or substantial duration in the c-method.

go/no-go cost in the c-method yielded Donders' RT pattern (a < c < b), whereas assuming a substantial cost yielded the RT pattern of Donders' students (a < c = b). Thus, whether the RT pattern of Donders or his students is obtained depends on the magnitude of a go/no-go cost, which differs among individuals (cf. Bender et al., 2016; Gomez et al., 2007). The simulation results provide proof of concept for Wundt's (1874) concern that the c-method involves a choice.

6. Summary and conclusions

The aim of the research reported in the present article was to commemorate the classic RT work of Donders (1868) by addressing an issue from his work that had remained unresolved up to now. This issue is whether speech repetition under the c-method involves a choice (i.e., whether or not to respond, which is an act of executive control), as held by Wundt (1874), or may not involve full discrimination, as held by Donders. The issue at stake in the historical controversy relates closely to issues in the modern study of RTs, including the exact relation between the b- and c-methods (e.g., Ratcliff et al., 2018; Vidal et al., 2011) and individual differences in the c-method (e.g., Bender et al., 2016; Gomez et al., 2007). First, my analysis of unpublished data from Donders (1865) on the repetition performance of his students revealed that the RTs for the b- and c-methods may not differ, supporting the view of Wundt. Second, my replication of Donders' classic study yielded the same RT pattern as Donders obtained for himself (i.e., a < c < b). This indicates that the classic RT pattern is replicable. However, my choice duration (b – c) was shorter than the discrimination duration (c – a), which suggests greater difficulty for me than Donders himself in making the go/no-go decision, in line with the view of Wundt. Third, my computer simulation using a modern computational model of speech repetition, WEAVER++, indicates that the RT pattern of Donders (a < c < b) or his students (a < c = b) may be obtained depending on the magnitude of the go/no-go cost, which differs among individuals (cf. Bender et al., 2016; Gomez et al., 2007). Thus, the simulation provides a proof of concept for the view of Wundt. To conclude, unpublished data, a replication, and modern modeling shed new light on an issue concerning speech repetition that remained unresolved for 150 years, underlining the importance of examining individual differences and executive control in task performance (cf. Shao et al., 2012; Sikora et al., 2016).

References

Bender, A. D., Filmer, H. L., Garner, K. G., Naughtin, C. K., & Dux, P. E. (2016). On the relationship between response selection and response inhibition: An individual differences approach. *Attention, Perception, & Psychophysics, 78*, 2420–2432.

Boersma, P., & Weenink, D. (2016). Praat: Doing phonetics by computer (version 6.0.12) [computer software] (Retrieved from) http://www.fon.hum.uva.nl/praat/.

Cattell, J. M. (1886). The time taken up by cerebral operations, part 3. *Mind, 11*, 377–392.

Cumming, G. (2014). The new statistics: Why and how. *Psychological Science, 25*, 7–29.

de Jaager, J. J. (1865). *De physiologische tijd bij psychische processen [The physiological time of psychical processes].* Utrecht: P. W. van de Weijer.

Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. *Psychological Review, 104*, 801–838.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168.

Donders, F. C. (1849). De bewegingen der hersenen en de veranderingen der vaatvulling van de Pia Mater, ook bij gesloten onuitzetbaren schedel regtstreeks onderzocht [The movements of the brain and the changes of the content of the Pia Mater, also directly investigated with a closed skull]. *Nederlandsch Lancet. Tijdschrift voor de Geneeskundigen Wetenschappen in Haren Geheelen Omvang, 5*, 521–553.

Donders, F. C. (1864). Zur Klangfarbe der Vocale [on the timbre of vowels]. *Annals of Physical Chemistry, 123*, 527–528.

Donders, F. C. (1865). *Snelheid der werking in 't zenuwstelsel [Speed of processing in the nerve system].* University Museum Utrecht (Archive Do 07.77).

Donders, F. C. (1868). Over de snelheid van psychische processen [On the speed of psychical processes]. *Onderzoekingen gedaan in het Physiologisch Laboratorium der Utrechtsche Hoogeschool, 1868–1869, Tweede reeks, II* (pp. 92–120). .

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica, 30*, 412–431 (Original work published 1868).

Draaisma, D. (2018). *The age of precision: F. C. Donders and the measurement of mind* (2nd ed.). Nijmegen: Donders Institute.

Gazzaniga, M. S., Heatherton, T. F., & Halpern, D. F. (2015). *Psychological science* (5th ed.). New York: Norton.

Geschwind, N. (1970). The organization of language and the brain. *Science, 170*, 940–944.

Gomez, P., Ratcliff, R., & Perea, M. (2007). A model of the go/no-go task. *Journal of Experimental Psychology: General, 136*, 389–413.

Helmholtz, H. (1850). Über die Fortpflanzungsgeschwindigkeit der Nervenreizung [On the speed of nerve conduction]. *Archiv für Anatomie, Physiologie und wissenschaftliche Medicin* (pp. 71–73). .

Jongman, S. R., Roelofs, A., & Meyer, A. S. (2015). Sustained attention in language production: An individual differences investigation. *Quarterly Journal of Experimental Psychology, 68*, 710–730.

Levelt, W. J. M. (2013). *A history of psycholinguistics: The pre-Chomskyan era.* Oxford: Oxford University Press.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22*, 1–38.

Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization.* New York: Oxford University Press.

Meyer, D. E., Osman, A. M., Irwin, D. E., & Yantis, S. (1988). Modern mental chronometry. *Biological Psychology, 26*, 3–67.

Pols, L. C. W., Tromp, H. R. C., & Plomp, R. (1973). Frequency analysis of Dutch vowels from 50 male speakers. *The Journal of the Acoustical Society of America, 53*, 1093–1101.

Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

Posner, M. I. (2005). Timing the brain: Mental chronometry as a tool in neuroscience. *PLoS Biology, 3*, e51.

Posner, M. I., & Raichle, M. E. (1994). *Images of mind.* New York: Freeman.

Raichle, M. E. (1998). Behind the scenes of functional brain imaging: A historical and physiological perspective. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 765–772.

Ratcliff, R., Huang-Pollock, C., & McKoon, G. (2018). Modeling individual differences in the go/no-go task with a diffusion model. *Decision, 5*, 42–62.

Roelofs, A. (1997). The WEAVER model of word-form encoding in speech production. *Cognition, 64*, 249–284.

Roelofs, A. (2014). A dorsal-pathway account of aphasic language production: The WEAVER++/ARC model. *Cortex, 59*, 33–48.

Sanders, A. F. (1998). *Elements of human performance: Reaction processes and attention in human skill.* Mahwah, NJ: Lawrence Erlbaum Associates.

Schmidgen, H. (2005). The Donders machine: Matter, signs, and time in a physiological experiment, ca. 1865. *Configurations, 13*, 211–256.

Shao, Z., Roelofs, A., & Meyer, A. S. (2012). Sources of individual differences in the speed of naming objects and actions: The contribution of executive control. *Quarterly Journal of Experimental Psychology, 65*, 1927–1944.

Sikora, K., Roelofs, A., Hermans, D., & Knoors, H. (2016). Executive control in spoken noun-phrase production: Contributions of updating, inhibiting, and shifting. *Quarterly Journal of Experimental Psychology, 69*, 1719–1740.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30*, 276–315.

Ulrich, R., Mattes, S., & Miller, J. (1999). Donders's assumption of pure insertion: An evaluation on the basis of response dynamics. *Acta Psychologica, 102*, 43–75.

Vidal, F., Burle, B., Grapperon, J., & Hasbroucq, T. (2011). An ERP study of cognitive architecture and the insertion of mental processes: Donders revisited. *Psychophysiology, 48*, 1242–1251.

Wernicke, C. (1874). *Der aphasische Symptomencomplex. Eine psychologische Studie auf anatomischer Basis [The aphasic symptom complex: A psychological study on anatomical basis].* Breslau: Cohn und Weigert.

Wundt, W. (1874). *Grundzüge der physiologischen Psychologie [Principles of physiological psychology].* Leipzig: Engelmann.