AMAZING PAPERS IN NEUROSCIENCE
The Legacy of the Kennard Principle

Danielle Elliott
School of Psychology & Neuroscience, University of St. Andrews, St. Andrews, Fife, Scotland KY16 9JP.

Research into neural plasticity has progressed rapidly over the last few decades, but the origins of this field lie in the early 20th century. In 1936, Margaret Kennard introduced the concept of brain plasticity in an animal model by studying the recovery of motor functions after performing brain lesions in infant and adult monkeys. It took until the 1970s for her work to be widely acknowledged. When her work did eventually make it into the limelight, this led to the synthesis of what scientists dubbed the 'Kennard Principle'. The Kennard Principle states that the younger an organism is, the greater and swifter recovery from brain injury will be. This principle itself is subject to controversy and debate; furthermore, it is based on a simplification of Kennard's original results. This article will explore Kennard's original 1936 paper, published in the American Journal of Physiology, and the context in which the Kennard Principle arose. Kennard's paper demonstrates early pioneering work within the field of behavioral neuroscience which provides a historical foundation for psychology and neuroscience undergraduates. Exploring the context in which the Kennard Principle arose also highlights the importance of tracing the origins of scientific principles and theories for students and researchers alike.

Key words: neural plasticity, lesion studies, Kennard Principle, motor function, behavioral neuroscience

Neural plasticity is an area of psychology and neuroscience that has been explored in a variety of brain areas since empirical studies surrounding it first emerged during the early 20th century. Neural plasticity refers to the ability of the brain to change and adapt to meet different functional needs throughout an organism's lifespan. Plasticity can be affected by a variety of factors. One of the most heavily debated of these factors is age. A common notion is that the brain's capacity for neural plasticity is greatest in younger individuals, meaning that younger organisms are more likely to make a faster and more complete recovery in the event of brain injury. This is sometimes referred to as the "young age plasticity privilege" (Dennis, 2010), though it is better known as the Kennard Principle, a term coined in the 1970s based on the work of neurologist Margaret Kennard (1899 – 1975). Revisiting Kennard's (1936) pioneering paper, which investigated factors affecting motor recovery in monkeys after motor and premotor brain lesions, reveals that age was only one of several factors found to influence recovery. Other factors include the size of the lesion, site of the lesion, and the time interval between lesions. Over time, however, the acknowledgement of these other factors has diminished. Belief in the Kennard Principle persists, and it continues to influence research and perspectives within a variety of scientific and medical fields. Kennard's (1936) original findings have been largely generalized and, to some degree, misinterpreted. Her paper offers a variety of interesting and ground-breaking findings that students can explore, giving them background knowledge on the field of neural plasticity whilst also giving recognition to work that has been oversimplified despite its importance to the field of neuroscience.

SOURCE SUMMARY

Kennard's (1936) study used behavioral observations to investigate the factors affecting recovery of motor function after premotor and motor brain lesions in monkeys. Specifically, the main factors investigated were the size of the lesion, the site of the lesion, and age. The effect of the time interval between operations was also taken into consideration. Many of these factors overlapped and were investigated simultaneously over several months. Behavioral observations mainly centered on hand and arm usage, such as measuring voluntary movements, gripping ability, and self-feeding.

To investigate the effect of the lesion's size on motor recovery, researchers removed either partial or entire sections of the monkeys' motor and premotor areas within one hemisphere. It was found that when the entire motor area was removed, thus impairing the representation of several body areas, recovery of motor function in the hands and arms slowed. If only a partial lesion was performed, including partial removal of just the hand and arm areas, motor recovery of the hand and arms was still impaired, but not as drastically as in the case of a full lesion. Furthermore, recovery was faster and more complete if the motor and premotor areas were lesioned at separate intervals rather than simultaneously. Some monkeys underwent lesions within the frontal lobe, and the impact of this on motor recovery was investigated. Lesions within this area did not affect recovery of motor functions. The effect of the lesion site was also investigated by performing both unilateral and bilateral lesions. This was found to be heavily influenced by the interval between operations and the age of the animal (infant or adult). It was found that, even in adult monkeys, voluntary power (which refers to the conscious utilization of limbs to move and grasp objects) was not completely eradicated if the interval between the lesions in the two hemispheres was more than four weeks; however, this recovery was minimal. An infant monkey that underwent a unilateral lesion showed very rapid recovery of all motor functions, and eventually developed along a normal trajectory.

When this same monkey later underwent a bilateral

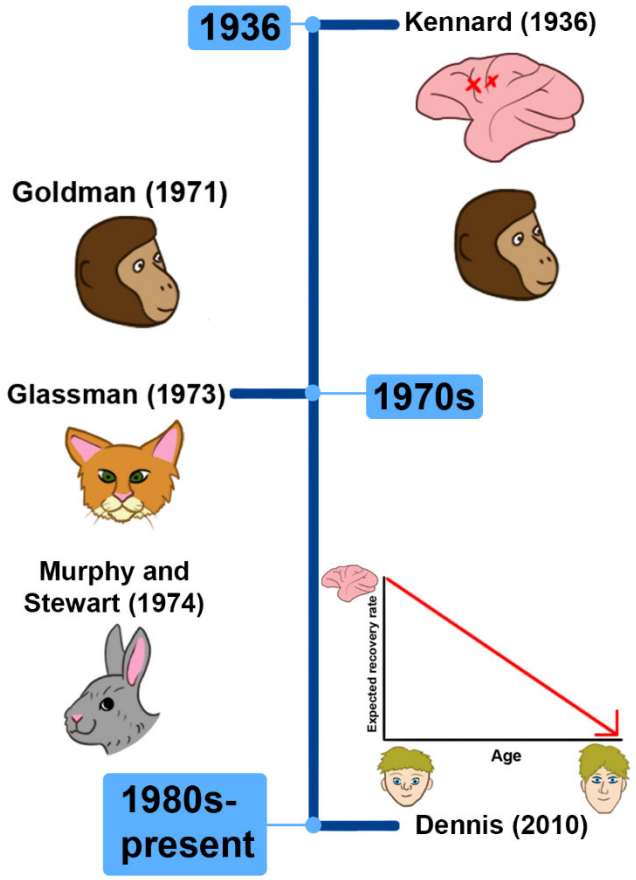

Figure 1. A graphical timeline of neural plasticity research and the Kennard Principle.

lesion at five months (still during infancy), motor recovery was significantly slower; the monkey showed slowed, impaired movement for about four weeks with gradual improvement. After four months, the monkey was once again able to perform many typical movements (walking, climbing, and gripping) with relative ease.

Kennard concluded that the age of the animal heavily influenced the overall motor function recovery and the speed of recovery, since infant monkeys recovered faster and more completely than adult monkeys. However, age was not the only factor to influence recovery; the size of a unilateral lesion also affected recovery. Smaller lesions led to more rapid recovery than larger lesions, and bilateral lesions caused permanent deficits across all ages. Finally, although infant monkeys expressed a smaller motor deficit and faster recovery than adults, some recovery was seen in adult monkeys if intervals between lesions were greater than four weeks. This shows that younger age does not always guarantee full recovery from brain damage and that adult brains can recover from damage if given enough time.

SUBSEQUENT WORK

In the decades after Kennard's (1936) paper, research on neurodevelopmental plasticity in animals re-emerged, resulting in a large body of work. Some studies were executed similarly to Kennard's (1936) work by observing behavioral outputs at different life stages after performing cortical lesions (see Goldman, 1971, outlined below). Other research investigated the effects of behavioral and environmental changes on brain physiology. For example, Blakemore and Cooper (1970) restricted the visual field of kittens to stripes of different orientations, then examined their behavioral responses and the functional properties of visual cortices in anaesthetized animals. They found that the animals were unable to visually detect objects that did not match the orientation of those in their previous environment, and neurons in affected areas were almost exclusively tuned to their exposed orientations. Furthermore, the neurons did not differentiate amongst objects of different orientations, as they would typically. Similarly, Hubel and Wiesel (1970) found frequent monocular deprivation reduced the growth and abundance of neurons in the lateral geniculate nucleus of kittens. These studies demonstrated the presence of an activity dependent critical period during visual system development, suggesting plasticity mechanisms may be intimately linked with neural activity as well as developmental stage. They also offer supporting anatomical evidence to the notion suggested by Kennard's (1936) behavioral observations that young age does not always guarantee sparing of function, and that this may be reflected on a neural level.

Goldman (1971) was another important study within the emerging field. This study investigated the effects of dorsolateral or orbital prefrontal cortex lesions in infant and adolescent monkeys. It was found that recovery from these lesions was not always enhanced by age. This was shown by the finding that infant and adolescent monkeys given orbital lesions were found to be equally impaired. Age did still enhance recovery in some instances—infant monkeys given dorsolateral lesions showed a greater degree of recovery than adolescent monkeys with the same lesion. However, comparison of the two lesioned groups of infant monkeys found that those with orbital lesions showed greater recovery over time than those with dorsolateral lesions, again suggesting that the lesion site, in association with age, plays a key role in recovery.

A similar paper from this period is by Glassman (1973). In this study, the sensorimotor cortices of cats were removed in infancy or in adulthood, then behavioral reflexes of the animals were measured. No enhanced recovery of reflexes was present in infant cats over adult cats. The paper continues to discuss that some behaviors appear more "spared" than others after lesions have been performed in infancy, but this varies depending on a variety of factors, such as—as stated before—the site of the lesion and the animal studied.

The papers outlined above are only a small number of examples of neural plasticity research that was published within the timeframe during which the Kennard Principle was established; however, further examples challenging the theory continued to emerge during this time period. Murphy and Stewart (1974) demonstrated no significant difference between the performance of adult and infant rabbits on a visual discrimination task when both groups had their primary visual cortex lesioned completely or incompletely. No significant differences were found between lesioned rabbits and normal rabbits during a brightness discrimination

task, suggesting not only that age does not necessarily predict performance (at least in a rabbit model), but that some visual functions are spared despite a visual cortex lesion. Kolb et al. (1989) found unilateral lesions of the frontal cortex had similar effects on both infant and adult rats' performance during a swimming task requiring spatial learning of the location of a submerged platform. Neonatal rats with a bilateral frontal lesion also performed worse on this task than adult rats with the same lesion, which could be due to no previous utilization of spatial learning and memory.

The research outlined above comes from a variety of animal models but the findings are similar across systems: 1) some brain areas may exhibit less plasticity than others in cases of environmental constraints; 2) the effect of age on recovery from brain lesions is variable; and 3) age is just one of many factors that influences recovery after a lesion. Despite conflicting evidence, the Kennard Principle became largely accepted as fact during this time, and still influences scientific fields in the present day. Examples of its influence can be seen in data gathered by Hart and Faust (1988). In that study 120 clinicians were asked to predict a patient's degree of impairment after they had experienced a head injury. When the patient was reported as an adolescent, they were judged to have greater impairments than when the patient was reported as being a child, which falls in line with the Kennard Principle. Webb et al. (1996) found the same results across a sample of participants from a wide range of medical and scientific fields (neurologists, speech therapists, and more). This shows the prevalence, as well as the longevity, of the Kennard Principle. Recent research continues to challenge the theory. For example, Fullerton et al. (2019) found the age of head injury occurrence in children and adolescents was associated with a deficit in executive functioning skills (namely impulse control), with children who suffered injury earlier exhibiting the greatest deficit. Anderson et al. (2005) also found that the degree of cognitive impairment was worse in children who had suffered traumatic brain injury at an earlier age, with older children showing better outcomes. This demonstrates that age does not always predict recovery in humans, or at least not in the manner that the Kennard Principle states. Whilst some clinical evidence suggests early unilateral brain lesions offer an advantage for reorganization of cortico-spinal projections over later lesions (Staudt, 2010), a vast body of evidence suggests a disadvantage of early brain lesions and injury on a variety of factors, including IQ (Duval et al., 2008) and later impairment of cognitive and psychological skills (Anderson et al., 2009), which refutes the Kennard Principle.

VALUE

Although there is more recent research demonstrating how brain lesions impact behavior, Kennard's (1936) paper is of value for several reasons. Firstly, it is a pioneering paper on the functional role of primate brain lesions and how each region contributes to behavior. Tracing an area of research back to its roots is a valuable technique—particularly for students—as it allows insight into how a field has developed over time, which can provide useful foundational knowledge. Secondly, and perhaps most significantly, this paper serves as the foundation for the Kennard Principle. This theory has clearly been influential, despite the fact that the principle itself is an oversimplification of the paper's original findings, with other important factors such as lesion site, size, and interval between lesions being overlooked in favor of age.

Delving further into Kennard's paper and the origins of the Kennard Principle highlights the importance of fact checking in research to ensure theories are based correctly on their evidence. It also offers insight into how misconceptions can arise within scientific literature. This is particularly important for students. In classroom settings, theories are often presented as concrete and their origins are left uncharted. Presenting this paper as the truth behind the principle would give students an appreciation of how work can be misunderstood over time and thus lead to inaccurate or poorly supported scientific theories. This element is also important for researchers, given how widely accepted the Kennard Principle has become.

Kennard's paper demonstrates effective research techniques that would be useful in teaching undergraduates about research design. The observed behaviors in the study are clearly laid out in the paper, and the way lesions affect behavior is made quite explicit. This makes the paper an approachable and interesting read for students and researchers alike. This paper is also some of the earliest work to employ such lesion techniques on animals, many of which would be difficult to carry out under modern ethical standards. Although Kennard's work is unable to be replicated, this arguably increases its value as a pioneering reference point in the history of neuroscience. The paper also provides valuable behavioral data underpinning plasticity principles. Although behavioral observation gives limited indirect insight into neural activity, it was the best available method at the time of publication. These factors contribute further to its value and serve as another example of how much neuroscientific research has developed, which is important knowledge for any students aiming to have a fuller understanding of the field.

AUDIENCE

Kennard's (1936) paper, in addition to the literature outlined above, would be a valuable addition to undergraduate psychology and neuroscience courses. Specifically, this paper would be most applicable in classes centered around behavioral neuroscience, as these papers generally focus on observing behavior after administering structural and functional neurological changes. Kennard's (1936) paper is of great value as an important milestone in this ever-expanding field, especially given the misinterpretations that arose in the decades after its publication. The paper could be used to teach students the value of tracing the origins of theories and not taking all information within the scientific community at face value. For classroom usage, educators could present students with the definition of the Kennard Principle, then instruct them to study the findings of Kennard's (1936) paper. Students could then compare the definition of the principle with the original findings. Once the class is clear on the distinction between Kennard's (1936) findings and the Kennard Principle, the class could be

divided into small groups, with each group presenting a different paper either supporting or opposing the Kennard Principle. After this, educators could hold a class discussion on whether the students believe in the Kennard Principle, and how the misconceptions regarding the principle arose. This would make for an interesting and lively discussion whilst also teaching students about neural plasticity research over time. Additionally, another classroom use could be for students to examine Kennard's (1936) experimental techniques and compare this to modern methods in order to show how techniques in neuroscientific research have developed. This would also give students a broader understanding of how methods for systematically 'deleting' brain regions within a model organism have changed. In Kennard's time, researchers could only generate permanent lesions. Today, researchers can reversibly inhibit activity in defined brain regions via pharmacological and optogenetic methods (Stuber and Mason, 2013).

A specific resource worth using alongside Kennard's paper to further students' understanding is an article by Dennis (2010), entitled 'Margaret Kennard (1899-1975): Not a 'Principle' of brain plasticity but a founding mother of developmental neuropsychology'. This article clearly articulates the timeline of Kennard's work from her 1936 paper and beyond, and explores subsequent work within the field and how the Kennard Principle emerged. As a companion piece to Kennard's (1936) paper, Dennis's publication frames Kennard's work as pioneering, and contrasts the Kennard Principle with her 1936 paper and the variety of research that followed.

CONCLUSION

In conclusion, teaching the Kennard Principle offers important foundational knowledge for the origins of the ever-growing research into brain plasticity, as well as how findings can be misconstrued over time within scientific fields. Its uses and benefits in a classroom setting are multiple, flexible, and would make for engaging and memorable content for many undergraduate students.

REFERENCES

Anderson V, Catroppa C, Morse S, Haritou F, Rosenfeld J (2005) Functional plasticity or vulnerability after early brain injury? Pediatrics 116:1374-1382.

Anderson V, Spencer-Smith M, Leventer R, Coleman L, Anderson P, Williams J, Greenham M, Jacobs R (2009) Childhood brain insult: can age at insult help us predict outcome. Brain 132:45-56.

Blakemore C, Cooper GF (1970) Development of Brain depends on Visual Environment. Nature 228:477-478. doi:10.1038/228477a0

Dennis M (2010) Margaret Kennard (1899-1975): Not a 'Principle' of brain plasticity but a founding mother of developmental neuropsychology. Cortex 46:1043-1059.

Duval J, Braun CMJ, Montour-Proulx I, Daigneault S, Rouleau I, Begin J (2008) Brain lesions and IQ: Recovery versus decline depends on age of onset. J Child Neurol 23:663-668.

Fullerton AF, Jackson NJ, Tuvblad C, Raine A, Baker LA (2019) Early Childhood Head Injury Attenuates Declines in Impulsivity and Aggression Across Adolescent Development in Twins. Neuropsychology 33:1035-1044. doi:10.1037/neu0000570

Glassman RB (1973) Similar effects of infant and adult sensorimotor cortical-lesions on cats' posture. Brain Res 63:103-110. doi:10.1016/0006-8993(73)90079-6

Goldman PS (1971) Functional development of prefrontal cortex in early life and problem of neuronal plasticity. Exp Neurol 32:366-387. doi:10.1016/0014-4886(71)90005-7

Hart K, Faust D (1988) Prediction of the Effect of Mild Head-Injury – A Message about the Kennard Principle. J Clin Psychol 44:780-782. doi:10.1002/1097-4679(198809)44:5<780::aid-jclp2270440519>3.0.co;2-1

Hubel DH, Wiesel TN (1970) Period of Susceptibility to Physiological Effects of Unilateral Eye Closure in Kittens. J Physiol 206:419-436. doi:10.1113/jphysiol.1970.sp009022

Kennard MA (1936) Age and other factors in motor recovery from precentral lesions in monkeys. Am J Physiol 115:138-146.

Kolb B, Zaborowski J, Whishaw IQ (1989) Recovery from Early Cortical Damage in Rats .5. Unilateral Lesions have Different Behavioral and Anatomical Effects than Bilateral Lesions. Psychobiology 17:363-369.

Murphy EH, Stewart DL (1974) Effects of neonatal and adult striate lesions on visual-discrimination in rabbit. Exp Neurol 42:89-96.

Staudt M (2010) Reorganization after pre- and perinatal brain lesions. J Anat 217:469-474.

Stuber GD, Mason AO (2013) Integrating Optogenetic and Pharmacological Approaches to Study Neural Circuit Function: Current Applications and Future Directions. Pharmacol Rev 65:156-170. doi:10.1124/pr.111.005611

Webb C, Rose FD, Johnson DA, Attree EA (1996) Age and recovery from brain injury: clinical opinions and experimental evidence. Brain Injury 10:303-310. doi:10.1080/026990596124476

Received January 4, 2020; revised February 29, 2020; accepted February 29, 2020.

The author would like to thank Dr. Bruce Johnson, Dr. Stefan Pulver, and her colleagues in the University of St Andrews MRes in Neuroscience program for helpful advice on the writing of this manuscript.

Address correspondence to: Danielle Elliott, School of Psychology and Neuroscience, St Mary's Quad, South Street, St Andrews, Fife, KY16 9JP. Email: de36@st-andrews.ac.uk