Animal behaviour

Negative impact of manganese on honeybee foraging

Eirik Søvik1,2, Clint J. Perry2,†, Angie LaMora1,‡, Andrew B. Barron2 and Yehuda Ben-Shahar1

1Department of Biology, Washington University in St Louis, St Louis, MO 63130, USA
2Department of Biological Sciences, Macquarie University, Sydney, New South Wales 2122, Australia

Anthropogenic accumulation of metals such as manganese is a well-established health risk factor for vertebrates. By contrast, the long-term impact of these contaminants on invertebrates is mostly unknown. Here, we demonstrate that manganese ingestion alters brain biogenic amine levels in honeybees and fruit flies. Furthermore, we show that manganese exposure negatively affects foraging behaviour in the honeybee, an economically important pollinator. Our findings indicate that in addition to its direct impact on human health, the common industrial contaminant manganese might also have indirect environmental and economical impacts via the modulation of neuronal and behavioural functions in economically important insects.

1. Introduction

The possible impact of environmental contaminants on human health is often measured only in terms of its direct impact on human biology [1]. By contrast, their possible indirect impact on human health via negative effects on other organisms is often ignored. Consequently, some environmental pollutants could have a significant effect on human health by affecting, for example, pollinators of important food crops even when present at levels that are not considered toxic.

Understanding the possible negative impact of metals such as manganese on insects could be important when considering the alarming reports on the continual loss of insect pollinators [2], which include the honeybee [3]. As honeybees bring nectar and pollen back to the nest where it is concentrated before being consumed [4,5], this can lead to the accumulation of contaminants such as metals in both honey and bee tissues [5,6]. Previous studies have shown that some metals can affect the responsiveness of honeybees to sucrose [7] without an impact on their visitation rates of contaminated flowers [8,9]. These data suggest that in areas where metals are present in nectars, bees are likely to carry them back to their hive. For example, elements such as selenium, aluminium and nickel can have an impact on behaviours of honeybees, bumblebees and other pollinators [7–10]. By contrast, the impacts of common anthropogenic metal pollutants such as manganese on bee health are not as well understood, despite their well-known effects on the physiology of plants [11] and vertebrates [12].

Previous work indicated that exposure to Mn2+ affects feeding behaviour of bees and flies [13,14] and is associated with changes in their brain transcriptome [15]. In addition, the concentration coefficient for Mn2+, defined as tissue accumulation relative to amounts consumed, is higher for honeybees than that of all other metals studied to date [16]. Because excessive Mn2+ levels have been found in commercial honeys, and its levels in honeys reflect the levels seen in the immediate environment [16,17], relatively small increases in environmental levels of Mn2+ could lead to significantly higher accumulation of this metal in honeybee tissues relative to other metal ions. As exposure to excessive...
Mn$^{2+}$ levels affect biogenic amine signalling in the mammalian brain [18], and biogenic amines are key modulators of honeybee foraging [19], we investigated the possible impact of dietary Mn$^{2+}$ on brain aminergic signalling pathways and foraging behaviour in honeybees.

2. Material and methods

We quantified levels of octopamine, dopamine and serotonin from the brains of honeybees (Apis mellifera) and fruit flies (Drosophila melanogaster) fed differing levels of Mn$^{2+}$ using high-pressure liquid chromatography as described elsewhere [20]. Mn$^{2+}$ was supplied in either 1.5 M sucrose (bees) or standard Drosophila medium (flies) over a period of 4 days. We tracked the individual bees treated with Mn$^{2+}$ using an RFID system that allowed us to track foraging activity throughout the lifespan. See electronic supplement material for additional details.

3. Results and discussion

We found that consumption of Mn$^{2+}$ by honeybees leads to a dose-dependent increase in brain levels of octopamine, dopamine and serotonin (figure 1a–c and table 1). These findings disagree with previous reports in mammalian models and the fruit fly, which showed Mn$^{2+}$ caused dopaminergic neurotoxicity and reduced levels of dopamine in the brain [21–23]. To confirm that our current observations were not unique to the honeybee, we treated fruit flies with sub-toxic levels of Mn$^{2+}$ and examined its impact on biogenic amine levels. As in the honeybee, we found that ingestion of 5 mM Mn$^{2+}$ by Drosophila caused an increase in brain levels of octopamine and dopamine, but not serotonin (figure 1d–f). Together, these results indicate that exposure to Mn$^{2+}$ at levels that are considered safe for humans can still affect insect behaviour.

**Table 1.** Linear-mixed regression models for the effect of Mn$^{2+}$ exposure on biogenic amine levels in honeybees.

<table>
<thead>
<tr>
<th>dependent variable</th>
<th>Mn$^{2+}$ concentration</th>
<th>d.f.</th>
<th>estimate</th>
<th>s.e.</th>
<th>$F$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>octopamine</td>
<td>1</td>
<td>33.04</td>
<td>11.48</td>
<td>8.238</td>
<td>0.00525</td>
<td></td>
</tr>
<tr>
<td>dopamine</td>
<td>1</td>
<td>97.16</td>
<td>20.61</td>
<td>21.904</td>
<td>0.00001</td>
<td></td>
</tr>
<tr>
<td>serotonin</td>
<td>1</td>
<td>43.11</td>
<td>10.42</td>
<td>16.894</td>
<td>0.00009</td>
<td></td>
</tr>
</tbody>
</table>

Mn$^{2+}$ levels affect biogenic amine signalling in the mammalian brain [18], and biogenic amines are key modulators of honeybee foraging [19], we investigated the possible impact of dietary Mn$^{2+}$ on brain aminergic signalling pathways and foraging behaviour in honeybees.

![Figure 1](image-url)
As increased biogenic amines in the honeybee brain are associated with precocious foraging [24,25], we next used the tracking of individual bees to study the effects of Mn²⁺ treatment on the ontogeny of bee foraging (figure 2a). Similar to our previous report [14], here we found that honeybees treated with 50 mM Mn²⁺ showed a precocious transition from in-hive behaviours to foraging ($\chi^2 = 25.4636$, d.f. = 4, $p < 0.0001$; figure 2b; electronic supplementary material, figure S1A). Surprisingly, precocious foragers completed significantly fewer foraging trips over their lifetime ($\chi^2 = 17.6$, d.f. = 1, $p < 0.0001$; figure 2c; electronic supplementary material, figure S1B), which suggests that long-term exposure of bee-hives to Mn²⁺ could negatively affect colony fitness. Furthermore, although all treatment groups increased the length of their foraging trips over time, the initial trips of 50 mM Mn²⁺-treated bees were significantly longer ($F_{6,393} = 85.55$, $p < 0.00001$, $R^2 = 0.51$, figure 2d; electronic supplementary material, figure S1C).

Our studies support a model in which Mn²⁺ treatment leads to an early transition to foraging by increasing brain aminergic signalling, which is in agreement with previous studies of biogenic amines in honeybees [19]. However, our findings are also in contrast to previous studies in mammals [18] and Drosophila [21], which indicated that Mn²⁺ exposure leads to dopaminergic neuronal loss, and overall reduced levels of dopamine in the brain. We do not yet understand the main reason for the differences between our current findings and previous reports. Noteworthy, the Mn²⁺ doses we have used in our studies were far below previously reported neurotoxic levels [21]. As a result, these previously published data together with our current findings suggest that the interaction of Mn²⁺ with biogenic amine signalling and behaviour comprises two phases: exposure to low Mn²⁺ levels leads to an increase in biogenic amine synthesis but, once above the neurotoxic threshold, it leads to a reduction in biogenic amine levels.

Our finding that Mn²⁺ treatment leads to extended initial foraging trips suggest that Mn²⁺-induced precocious foraging might be associated with decreased navigational abilities or lower physical fitness. As increase in time spent on individual foraging flights has previously been linked to declining health and decreased navigational abilities of foragers [26], our findings further support the hypothesis that exposure to even low levels of Mn²⁺ could affect the long-term health of bees. As Mn²⁺ induces precocious foraging and the foraging performance of precocious foragers is significantly lower than typical-age foragers [27], our data indicate that in addition to the increased environmental pressures from parasites, pathogens, insecticides and modern agricultural practices on the health of pollinators [2], it is important to consider other potential anthropogenic factors such as metal pollution as possible risk factors. Consequently, better understanding of these factors would lead to improved risk assessment, and improved management practices of pollinators and other beneficial invertebrates.
References


